The application of sewage sludge to agricultural land in Scotland: risks and regulations

A report for Scottish Environment LINK by Thomas Easton

April 2023

Executive Summary

This report was written as part of a 3 month PhD student placement with Scottish Environment LINK. The recommendations reflect the views of the author.

The application of treated sewage sludge (biosolids) to agricultural land is a common practice in many countries. It is a seemingly sustainable use for a solid waste produced in Scottish wastewater treatment plants. The practice provides a low cost supply of nutrients and organic matter to farms and reduces Scotland's reliance on environmentally damaging mined chemical fertilisers. It should be noted that treated sewage sludge represents a small percentage (around 2%) of the total tonnage of bulky organic and inorganic waste materials applied to Scottish land[1], and that materials are treated and applied to land in compliance with existing standards.

Treated sewage sludge is contaminated with organic chemicals and microplastics. Without effective source control, these pollutants are applied to land alongside the fertilising sludge. Priority must be given to preventing these contaminants entering the waste water system, for example through banning the use of micro plastics, requiring washing machines to be fitted with filters and banning the use of PFAS[2]. However, given the sources are many and varied, it is also essential that the regulation of sewage sludge and its application is improved. The levels of many harmful chemicals are not covered by the current regulations. Sustainability benefits of nutrient recycling and waste reduction therefore come at the price of contaminated soil and potential accumulation of pollutants in Scottish farmland, crops and food sources.

[1] https://www.sepa.org.uk/media/594166/sepa-materials-to-land-report-v2.pdf *'Of the thirteen broad types of materials considered in the project, animal manures and slurries are by far the most important, making up around 87% of the total tonnage of materials applied in Scotland …….. The next most important materials under consideration (in tonnage terms) are anaerobic digestates (5.7% of the total tonnage of all materials applied annually), wastes from distilleries and breweries (3.5%), composts (1.7%) and sewage sludge (1.7%). '*

[2] Fidra. (2023).

M. C. Society, "Sewage sludge: Why we need to stop pollution at source," (2021).

In Scotland, there is a complex outdated regulatory system for the application of waste materials to agricultural land and the large range of stakeholders across industries matches this complexity. Alongside their use as organic fertilisers in agriculture, organic waste materials can also be used in land reclamation and to generate energy (e.g., biogas during anaerobic digestion treatment processes or as feedstocks in energy-from-waste incinerators). Sewage sludge is classified as a waste but its application to agricultural land is currently covered under different legislation (Sludge (Use in Agriculture) Regulations) to other waste materials. Changes to regulations will have knock on effects in the water, waste handling, and farming industries as well as in the natural environment, which must be considered.

The proposal for an Integrated Authorisation Framework (IAF) in Scotland intends to overhaul outdated waste handling regulations including those covering the application of sewage sludge to agricultural land. Consultation on the proposed framework will be open for comment later in 2023. This offers the opportunity to call for tighter regulation of contaminants present in waste materials which may harm Scotland's soils and present a risk to health. This report provides an overview of this complex issue and seeks to summarise the key considerations that new regulation of sludge application to agricultural land should take into account.

Key recommendations for a response to consultation on waste handling regulation:

- Incorporation of existing voluntary schemes (Biosolids assurance scheme and Safe Sludge Matrix) into law.
- Regulatory bodies should be given increased power to audit and enforce compliance with contaminant levels of sludge and soils.
- Based on the evidence provided in Scottish Government Commissioned reports, monitoring of key chemical contaminants should be carried out in soils and sludge.
- Based on the precautionary approach and new evidence suggesting that contaminants in biosolids are harmful to the environment, a call for threshold limits for emerging contaminants and microplastics should be made due to current unknown levels of risk to the environment.
- Alternatives to sludge spreading to agricultural land should be explored and prioritised if the level of risk cannot be defined based on current knowledge.

Contents

1. Introduction

This report was written as part of a 3 month PhD placement and aims to review evidence of the positive and negative impacts of sludge application to agricultural land in Scotland and provide useful information for the IAF consultation. Many thanks to Dr. Joanna Cloy from Fidra for providing advice during the PhD placement and report production, and Dr. Alan Cundill from SEPA for comments on an earlier draft of this report. The conclusions and recommendations reflect the views of the author.

This report is based on evidence from published literature and discussions with stakeholders. Literature review of scientific content was conducted using the University of Edinburgh library tool DiscoverEd. Results based on keywords related to each topic of interest were selected based on relevance to Scottish soil and wastewater content. The UK and Scottish policy review was written with reference to the Scottish Government Sludge Review documentation and discussion with SEPA representatives as well as published documentation from the European Commission. Stakeholder overview was prepared with reference to available published documentation from individual organisations and also discussion with representatives carried in virtual meetings.

2. Sewage sludge and its treatment

Sewage sludge is the semi-solid waste produced during wastewater treatment. It can be generated through various processes. Physical bar screens remove large solid debris in the wastewater, which go to landfill. Smaller solids such as organic matter, food waste, textiles and paper settle in sedimentation tanks where they form the primary sludge[3]. The clarified wastewater is treated biologically (through aerobic digestion in bioreactors or anaerobic digestion through closed digesters or open lagoons) to form a secondary sludge comprised of remaining solids, microorganisms and activated waste biomass.

Disposal of this sewage sludge at sea was the preferred end of life solution until this practice was banned in the late 1990s[4]. In 1990, 70.1% of Scotland's sewage sludge was being dumped at sea[5]. Since the ban, this has changed as shown in figure 1 below.

[3] A. Hussain, in *Advanced Design of Wastewater Treatment Plants: Emerging Research and Opportunities*. (IGI Global, Hershey, PA, USA, 2019), pp. 255-292.
[4] The ban was applied across the EU and was set out in the UWWTD, requiring Member States to phase out disposal to sea by 31 Dec 1998

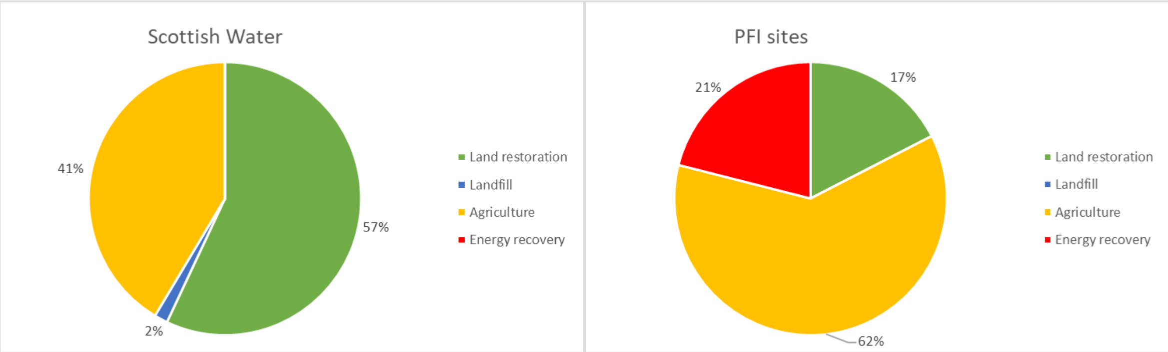

Figure 1: Fate of biosolids produced in Scottish treatment sites in the 2021/22 reporting year operated by Scottish Water (left) and contracted PFI sites (right) data provided by Scottish Water

Figure 1 presents the destination of sludge from Scottish water and PFI (PPP) sites. According to Scottish Water, 245,000 wet tonnes of wastewater bio-resource was produced in Scotland in the 2021/22 annual period. The majority (142,297 wet tonnes) originates from public-private partnership (PPP) treatment sites not operated by Scottish Water, with 103,281 wet tonnes produced by Scottish Water.

2.1 Treatment of Sewage Sludge

Raw sewage sludge is treated in Scotland by a number of different processes. After secondary sludge treatment in bioreactors, tertiary sludge treatment is carried out in order to remove / reduce contaminants and produce useful products and is a prerequisite for applying the sewage sludge to land. Each treatment results in a different quality of biosolids material termed conventional or enhanced treated. In Scotland, most sludge is treated using one of the methods presented in Table 1.

Most commonly applied to sewage sludge, as well as other materials such as animal manures and food waste, is Anaerobic Digestion (AD) where biological breakdown of the organic matter in sludge is carried out at ~35 ˚C and has the benefit of producing biogas[6]. Advanced anaerobic digestion (AAD) adds a thermal hydrolysis pre-treatment step. High pressure heating up to 200 ˚C improves the bioavailability of the organic content in sludge and improves the efficiency of the subsequent biological treatment and biogas production[7]. Thermal drying reduces the wet volume of sludge significantly (usually reducing moisture content to around 70%) and is carried out at high (~ 450 ˚C) temperatures. Dried sludge cake or pellets that are produced in Scotland are generally used as a waste derived fuel in the cement manufacturing process and out of spec pellets can be applied to agricultural land. This is not the same as incineration or pyrolysis for energy recovery. Liming involves heating sludge over 55 ˚C under extremely alkaline conditions.

[6] Y. Zeng *et al.*, Evaluating the Effects of Different Pretreatments on Anaerobic Digestion of Waste Activated Sludge Containing Polystyrene Microplastics. *ACS ES&T Water* **2**, 117-127 (2022).
[7] A. L. Nascimento *et al.*, Sewage Sludge Microbial Structures and Relations to Their Sources, Treatments, and Chemical Attributes. *Frontiers in Microbiology* **9**, (2018).

Table 1: Methods for conventional and enhanced sewage sludge treatment applied in Scotland

Treatment method	Material produced, dry matter	Treatment requirements met*
AAD, followed by de-watering	biosolids cake, 30%	Enhanced
Drying (no AD or stabilisation)	biosolids pellets, 95%	Enhanced
Liming and de-watering	biosolids cake, 40%	Enhanced
AD, followed by de-watering	biosolids cake, 25%	Conventional
AD, followed by de-watering and drying	biosolids pellets, 95%	Enhanced
AD of liquid sludge	Liquid, 4%	Conventional

*Conventionally treated sludge is expected to have a $2\log_{10}$ (or 100-fold) reduction in *E. coli* while enhanced treated should reach $6\log_{10}$ (or 1,000,000-fold) removal of *E. coli* and 100% removal of *Salmonella*[8]

Determining whether sludge contaminants present a risk to human health if spread on land is challenging. Risk describes the probability of adverse effects occurring and is a function of the inherent toxicity of the chemical or pathogen, how much is in the environmental medium and how much exposure to humans occurs. The type of treatment applied has implications for the quality of the final sludge in terms of contaminant load and therefore the risk level it poses. Enhanced and conventionally treated sludge can be applied in different circumstances under the requirements of the Safe Sludge Matrix (see section 3.1).

Although enhanced sludge treatment effectively reduces pathogens and bacteria, there is far less certainty about its effectiveness in reducing chemical contaminants such as microplastics. A comparison of the effectiveness of key sludge treatment methods used in Scotland in removing a selection of chemical contaminants[9] is presented in Table 2:

[8] Scottish Government, *Spreading of sewage sludge to land* (2016 https://www.gov.scot/publications/impacts-human-health-environment-arising-spreading-sewage-sludge-land-cr-2016-23-project-summary/pages/2/).
[9] https://www.gov.scot/publications/impacts-human-health-environment-arising-spreading-sewage-sludge-land-cr-2016-23-project-summary/documents/

Table 2: Literature evidence of removal of chemical contaminants by sludge treatment

	Removal efficiency of sludge treatment				
Chemical pollutant	**Anaerobic Digestion**	**Drying**	**Thermal hydrolysis**	**Liming**	**Reference**
Atenolol	41 - 63 %	No evidence	No evidence	No evidence	(*53, 54*)
Triclocarban	10 - 11 %	No evidence	99%	No impact	(*53, 55, 56*)
Benzothiazole	No evidence	No evidence	No evidence	No evidence	
PBDE 99 & 209	21 - 24 % & 31 - 64 %	No impact	No evidence	No evidence	(*57, 58*)
PCB 118 & 138	18 – 20 %	No evidence	No evidence	No evidence	(*59, 60*)
Cyclomethicone 5 & 6	~59 % & No removal	No evidence	No evidence	No evidence	(*61, 62*)
Nonylphenol (NP) and NP2EO	2.6 - 100%	No evidence	No impact	No evidence	(*63, 64*)

A lack of comprehensive literature and contradictory results in laboratory experiments (e.g., In the case of nonylphenol removal by AD) makes it difficult to determine the removal of chemical contaminants prior to land application. Although treatment may be capable of attenuating the concentration of some organic contaminants, others may pass through unchecked and be applied to land in the same amounts they are present in the raw sludge. Regular testing of soil treated with sludge would provide valuable data to understand the fate of these chemical contaminants and not only help develop an understanding of chemical fate but also a clear indicator of potential risk to health from chemical exposure.

2.2 Application to agricultural land

Sewage sludge is a nutrient rich waste material with value as a fertiliser due to high nutrient and organic matter concentrations. Its application to agricultural land is encouraged in the UK to maximise the use of nutrients / organic matter and promote a circular economy. It is recognised by the EU and the UK Government as the Best Practicable Environmental Option in most circumstances. Captured in the sludge alongside beneficial components are microplastics and organic pollutants. When the sludge is applied to agricultural land, these contaminants enter the soil, potentially affecting aquatic and terrestrial life, food and grazing crops (and therefore human health) and the long-term soil health. It should be noted that sewage sludge makes up a small proportion of material that is applied to agricultural land, and other materials also contain contaminants.

The benefits of sewage sludge application to land are clear with valuable material otherwise going to waste or even requiring significant energy inputs to incinerate and dispose of safely. However, this is coming at a potential cost of land pollution. Many stakeholders call for tighter regulation on the content of sewage sludge applied to agricultural land until the risk of land contamination can be proven safe. The waste handling policy landscape in Scotland is set to change in the near future under the Integrated Authorisation Framework, giving a potential opportunity to update the Sludge (Use in Agriculture) Regulations.

Land reclamation projects also utilise sewage sludge as it provides organic matter and nutrients to areas of very poor soil quality. Although this has been a major alternative route for use of sewage sludge in Scotland, this outlet for sludge use is set to decline as most of these restoration projects involve former opencast coal sites, the restoration of which is nearing completion. Regulation for this type of land application, as well as use in forestry, is distinct from sludge use in agriculture and is not discussed in this report.

2.3 Energy recovery and nutrient extraction from sewage sludge

Emerging concerns around the quality of biosolids has stimulated recent interest in treatment and energy from waste technologies that claim to reduce or destroy contaminants such as microplastics and PFAS.
Complete combustion of organic wastes such as sewage sludge through incineration is carried out at temperatures over 800 ˚C but moisture must be removed first through dewatering or thermal drying. For maximum energy recovery, sludge cake must have moisture contents <70%, otherwise auxillary fuel may be required for combustion. The heat generated from flue gases produced during incineration is used to create energy but simultaneously, harmful gases (such as nitrogen dioxide and sulfur dioxide) are generated and require treatment prior to release. Incineration can be considered a viable end of pipe solution which destroys chemical contaminants and pathogens if a high temperature is used although this would need to be tailored to the identity and quantity of contaminants present in the sludge. However, incineration can generate other organic contaminants (e.g. dioxins) in some circumstances, which accumulate in the ash residues and result in it being dangerous to handle, treat and use on land; furthermore, high process cost and energy requirements are not balanced by the generation of a low-value ash[10].

An alternative to incineration is the energy recovery and decomposition of sludge in the absence of oxygen via pyrolysis. Pyrolysis of dried sludge case is carried out up to temperatures of 800 ˚C and key by-products are biochar, bio-oil and biogas (mainly composed of methane and hydrogen) . The quality and quantity of useful byproducts depends on the composition of the sludge itself and careful optimisation of the pyrolysis conditions. Heavy metal contamination can impact the quality of the biochar produced and the complex nature of the pyrolysis process may limit the application in some cases, but this treatment brings advantages in reducing the production of harmful gaseous pollutants and potentially useful byproducts. Gasification is a similar energy-from-waste decomposition process carried out at a higher temperature up to 1000 ˚C in a partially oxygenated environment and carries similar advantages and disadvantages to pyrolysis.

[10] K. S. Jumoke Oladejo, Xiang Luo, Gang Yang and Tao Wu. (Sludge Processing, 2020).

An option to recover valuable nutrients from the sewage sludge without applying it to agricultural land directly is an area of intense research. As a key example, Germany has embraced technologies for phosphorus recovery from sludge[11]. In amended German sludge ordinance introduced in 2017, WWTP operators have transition periods for implementing phosphorus recovery from sewage sludge. Transition periods are dependent of population equivalents being served but in general, medium and large sized WWTPs will not be able to apply biosolids directly to agricultural land and must apply a phosphorus recovery process (unless levels are too low for viable recovery). The most effective method of phosphorus recovery is wet chemical recovery from sewage sludge ash/biochar after incineration or pyrolysis. Driven by the need for careful soil nutrient management and control of fertiliser application, public perception of sludge to land and circular economy benefits, future phosphorus recovery will be required for all German sewage sludge, phased in from 2029.

3. Current Policy Context

3.1 Regulation in Scotland covering sludge application to agricultural land

The UK regulatory environment is complex with sludge falling under a number of definitions both as a fertiliser and as a waste.

As an organic matter fertiliser, sludge is subject to the storage and spreading controls under the Water Environment (Controlled Activities) (Scotland) Regulations 2011. Furthermore, EU Nitrate Directive requirements are presented in the UK Code of Practice for the Agricultural Use of Sewage Sludge to which farmers voluntarily adhere. Together, these requirements include limits on the amount of nutrients added to soil, stipulations on where fertiliser can be spread to avoid runoff to water etc. and specific weather conditions under which spreading is authorised. These regulations do not include mention of pollutants, emerging contaminants or microplastics.

Sludge quality is covered to some extent by legislation in the 1989 Sludge Use in Agriculture regulations (SUiAR). Controls are present to account for pH and heavy metal contamination including Cr, Cd, Cu, Pb, Hg, Ni, Zn. The SUiAR stipulates that soil is tested before first application and any biosolids are tested at 6-month intervals, specifying limits for the average annual rate of addition for each element that is analysed. Records of testing results are retained and may be audited by the Scottish Environmental Protection Agency (SEPA).

The Safe Sludge Matrix (aka ADAS Matrix) outlines voluntary best practice guidance to be followed by all UK water companies. It does not allow spreading of untreated sludge in any circumstances but does not specify what treatment types are to be used. Treatment generally involves advanced anaerobic digestion, thermal drying or lime pasteurisation. Treatment can be 'conventional' (99% ecoli removal) or 'enhanced' (99.999% ecoli removal and Salmonella totally removed). Although the matrix does not mention any other pollutants, treatment may

[11] T. C. Sichler, C. Adam, D. Montag, M. Barjenbruch, Future nutrient recovery from sewage sludge regarding three different scenarios - German case study. *Journal of Cleaner Production* **333**, 130130 (2022).

reduce the levels of many contaminants as discussed in Section 2.1. Conventionally treated sludge can only be used on land where combinable or animal feed crops are grown or on grassland/forage cropland, with further restrictions on subsequent grazing.

Based on the requirements of the Safe Sludge Matrix, the Biosolids Assurance Scheme (BAS) is a voluntary scheme set up in 2015 by Assured Biosolids (not for profit run and owned by UK water and sewerage companies) and is intended to compliment the SUiAR by introducing additional requirements for those producing, treating, transporting, storing, spreading and using sewage sludge. This includes requirements relating to risk assessments, record keeping and controls for source materials, treatment, sampling and analysis of the treated sludge products and receiving soils. For example, in relation to soil testing, BAS introduced a specific requirement for nutrient testing, expanding the range of potentially toxic elements testing requirements and increasing the frequency at which operators must test the soils.

Biosolids are transported as a waste material and hauliers must hold licences and be registered as transporters of waste with SEPA. Waste Management Licensing (Scotland) Regulations cover processes that see sludge imported (such as large sludge treatment sites used to treat quantities of sludge from smaller sewage treatment works). The requirements of these licenses cover odour management and stipulate that no risk to water, air, soil, plants or animals occurs by their handling. Storage of sludge falls under the Paragraph 8 waste exemption whereby handlers are required to notify SEPA of storage locations and intended use.

Sludge application to land in Scotland was reviewed in a Scottish Government report [12]. The report gives an overview of sludge production in Scotland, reviews the regulatory environment under which it is handled and provides an initial assessment of the risk to human health by a number of common pollutants present within it. The report recommends the incorporation of the Safe Sludge Matrix into law in Scotland as well as significant changes to the way SEPA regulates and permits sludge storage and handling. Complete assessment of the risk to health could not be carried out due to insufficient data but most of the chemical contaminants considered were deemed to not pose a high risk to receptors at the levels expected in soil. Despite this, the risk of accumulation and uptake into food crops was highlighted. Monitoring of chemical pollutants in sludge is clearly key to ensuring levels remain at a safe minimum and the report recommends introducing robust testing and monitoring in Scotland.

Subsequently, the Scottish Government commissioned a report by the James Hutton Institute[13]. It concluded that: Overall, the impacts of sewage sludge (when used correctly) on physical health outcomes are likely to be minimal and not significantly different to other organic soil amendments (e.g. animal manures). Impacts associated with quality of life and well-being (such as annoyance from malodour) can, however, be much more acute. These impacts are not exclusive to sewage sludge but are associated with a range of industrial and agricultural practices. Physical health risks have been by and large managed through

[12] https://www.gov.scot/publications/review-storage-spreading-sewage-sludge-land-scotland-sludge-review-final/
[13] https://www.gov.scot/publications/foi-202100243526/

improvements in sludge treatment processes as well as best practice; however, the impacts on well-being have been largely ignored. It should be noted that 'emerging' potentially hazardous agents is an ever-changing situation. The main hazards of concern today are likely to be superseded in the future. Since the 2008 report (SNIFFER 2008), the focus has moved from inorganic contaminants towards organics and pharmaceuticals, as well as 'novel' pathogens and antimicrobial resistance. Over the next 10 years, a different set of hazards are likely to become priority. Protecting public and environmental health is an on-going process.
It also highlights as a ‘key finding’ that:
A watching brief should be maintained to assess new information on the hazards included in this study, as well as to identify any further potential hazards as they emerge.

3.2 Broader UK activity

In England and Wales, a 2020 Environment Agency policy paper on a strategy for safe and sustainable sludge use highlighted concerns around the outdated SUiAR being unfit for purpose and requiring updating[14]. Covering England and Wales, the strategy brings sludge use under Environmental Permitting Regulation, making SUiAR obsolete. It is not clear what action on contaminants and microplastics will be taken but the paper acknowledges that emerging risks associated with organic and inorganic chemicals, anti-microbial resistance and plastics should be assessed. The paper recognises the need to also work across the UK via the Chemical Investigation Program (CIP).

The UK Water Industry Research (UKWIR) Chemical Investigation Program (CIP) and CIP Scotland are actively working on understanding trace level chemical pollution in the water environment and increase the evidence base for regulatory and legislative decisions[15]. It has recently included significant monitoring of biosolids quality[16]. The CIP2 Scotland Sludge report carried out sampling at Galashiels anaerobic digestion sewage treatment centre over a 13 month period. Metals and pharmaceuticals were sampled and compared to the EU Sludge Directive 2011 working draft limits. The contaminants in question were found to be below these limits.

The recently published UKWIR CIP3 report summarises biosolids data for samples taken from Scottish Water’s Seafield advanced anaerobic digestion (AD) and Galashiels AD sludge treatment centres between September 2021 & September 2022. Lower concentrations of contaminants were found for these Scottish samples compared with biosolid samples from sludge treatment centres across England and Wales. Out of a total of 173 substances

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[14] Environment Agency, *Environment Agency strategy for safe and sustainable sludge use* (2020 //www.gov.uk/government/publications/environment-agency-strategy-for-safe-and-sustainable-sludge-use/environment-agency-strategy-for-safe-and-sustainable-sludge-use).
[15] https://ohbp.org/2021/07/01/chemical-investigation-project-3-scotland-cip3-scotland-started-in-april-2021/
[16] M. J. Gardner, S. D. W. Comber, B. Ellor, Summary of data from the UKWIR chemical investigations programme and a comparison of data from the past ten years' monitoring of effluent quality. *Science of The Total Environment* **832**, 155041 (2022).

analysed, 19 substances were below the limits of detection for all UK analyses conducted[17]. The current CIP4 programme also includes sludge investigation.

3.3 European Union activity

In the EU, a number of regulations currently cover sludge use on agricultural land. Namely, the EU Sewage Sludge Directive (SSD 86/278/EEC) on agricultural use of sludge, Water Framework Directive 2000/60/EC on water protection, Directive 91/271/EEC on urban waste water treatment, Directive 96/61/EC concerning integrated pollution prevention and control, Directive 99/31/EC on the Landfill of Waste and Integrated Pollution Prevention and Control (IPPC) Directive (2008/1/EC).

The Urban Waste Water Treatment Directive encourages sludge reuse wherever appropriate and puts specific requirements on sludge use in agriculture[18] This directive is to be revised and a re-case version has been published with proposes to amend the Article on sludge so that sludge management routes maximise preventions, re-use and recycling of resources and minimise the adverse effects on the environment[19]. The European Commission held a public consultation and targeted stakeholder consultation on the Evaluation of the Sewage Sludge Directive (SSD 86/278/EEC) seeking to revise its content and update regulation. A working draft outlining some elements of the ongoing consultations is available including revised limits on heavy metals previously proposed in 2011[20]. An Exploratory Study report was published in 2022 to support the evaluation[21]

While the SSD places limits on heavy metals and care of nitrogen and phosphorus levels, it has some perceived shortcomings. The SSD was originally intended to promote the use of sewage sludge in agriculture. It prohibits the use of untreated sludge (unless directly injected into soils) and defines treated sludge as that which has undergone biological, chemical or heat treatment, long-term storage or any other appropriate process so as to significantly reduce its fermentability and the health hazards resulting from its use. The directive negates to control emerging contaminant and microplastic loads in applied sludge. The regulation was first introduced in 1986 and the EC consultation, mentioned above, investigates if it is still fit for purpose.

In 2014, the SSD was reviewed under the "Ex-post evaluation of certain waste stream directives" which notably highlighted issues around pollutants of emerging concern and microplastics. Since the directive was developed, scientific understanding of many of the potential problems associated with sewage sludge application to land has advanced and many call into question the relevance of some directive points. The EC evaluation aims to

[17] The National Chemical Investigations Programme 2020-2022 Volume 6 - Biosolids Products Data Report (ukwir.org)
[18] European Commission, *91/271/EEC concerning urban waste water treatment* (1991 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31991L0271).
[19] Proposal for a revised Urban Wastewater Treatment Directive (europa.eu)
[20] EUROPEAN COMMISSION, *WORKING DOCUMENT SLUDGE AND BIOWASTE* (2010).
[21] Support to the evaluation of the Sewage Sludge Directive – Publications Office of the EU (europa.eu)

complement previous reviews and advise on the need to revise the SSD, much like the case in the UK with the strategies being developed by SEPA and the Environment Agency (Section 3.1).

It should be noted that treated sewage sludge represents a small percentage (around 2%) of the total tonnage of bulky organic and inorganic waste materials applied to Scottish land[22].

4. Stakeholder Overview

Sewage sludge use in agriculture involves a large range of stakeholders across farming, food and drink, energy and waste management industries as well as those concerned with the environmental implications of its application to land. Figure 2 summarises key stakeholder groups identified in Scotland. Stakeholders are grouped by their perceived power to implement change in the way sludge to land is regulated as well as the perceived level of incentive each group has for implementing this change.

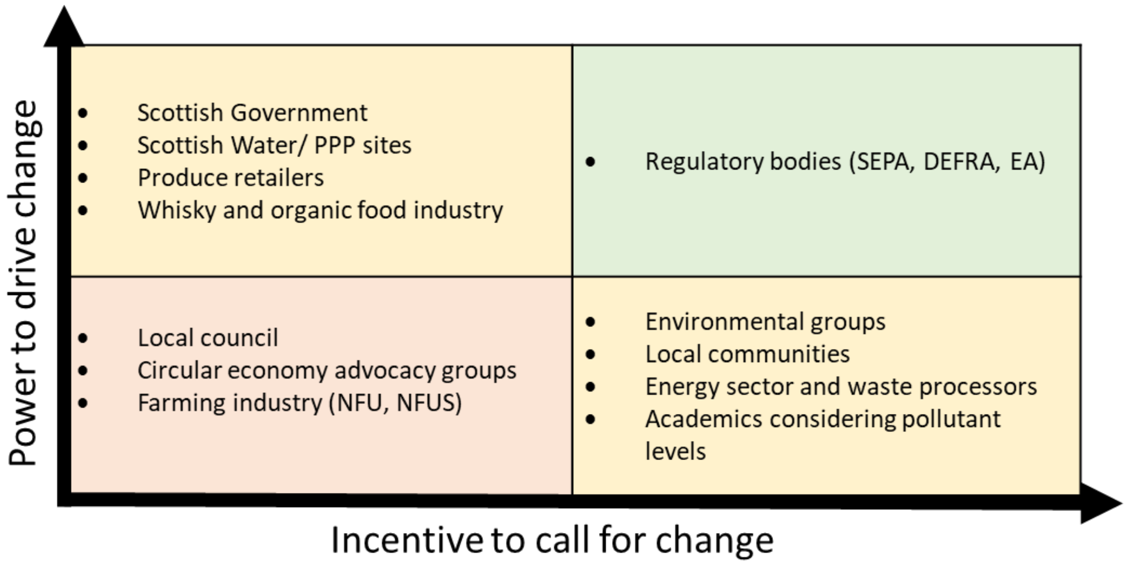

Figure 2: Examples of stakeholders arranged by a) power to drive or promote reform in how sludge to land is regulated and b) incentive to change current regulations.

Note that other potential stakeholders include Farm Assurance Schemes such as Red Tractor, Quality Meat Scotland, Food Standards Agency Scotland and Zero Waste Scotland. Minimising risk to health, public perception and maintaining Scotland's reputation as a leader in human and environmental health are the key messages put forward by Scottish Government in the Sludge Review conclusions[23]. The government broadly supports a transition to a circular

[22] https://www.sepa.org.uk/media/594166/sepa-materials-to-land-report-v2.pdf *'Of the thirteen broad types of materials considered in the project, animal manures and slurries are by far the most important, making up around 87% of the total tonnage of materials applied in Scotland …….. The next most important materials under consideration (in tonnage terms) are anaerobic digestates (5.7% of the total tonnage of all materials applied annually), wastes from distilleries and breweries (3.5%), composts (1.7%) and sewage sludge (1.7%). '*

[23] Scottish Government, *Spreading of sewage sludge to land* (2016 https://www.gov.scot/publications/review-storage-spreading-sewage-sludge-land-scotland-sludge-review-final/

economy and energy sustainability in line with their ongoing commitments and specifically the Circular Economy Bill. Re-use of sewage sludge is in line with the vision of zero waste in Scotland. The high cost of an overhaul to treatment systems and the fact that the current system is perceived as the environmentally friendly option is a major barrier to government action as is the lack of clear evidence when it comes to levels of contaminants leading to increased public risk.

Water companies produce, handle and oversee the recycling/recovery or disposal of waste sewage sludge. Scottish Environment LINK discussions with Scottish Water shed light on activity in this area. Scottish Water actively fund research on understanding contaminants present in sludge and treatment improvement with a long-term goal of bringing contracted Public Private Partnership sites back under their control and updating processes at these sites. Economic drivers and a lack of research evidence and regulation to cover emerging risks relating to contamination of biosolids are barriers to change in current processes. Awareness of the potential chemical contaminant levels in sludge is high and Scottish Water are involved in the UKWIR Chemical Investigation Program (CIP) and CIP Scotland. Benefits of sludge recycling to water companies and sludge processors mainly lie in energy recovery potential and having agricultural, forestry and land reclamation outlets in line with their circular economy goals.

The storage and stockpiling of sewage sludge is authorised under the Waste Management Licensing (Scotland) Regulations but, with the exception of these activities, SEPA as the regulators have limited power under the SUiAR. In addition, there is limited value gained from monitoring the use of sludge, as sludge use is not permitted directly, SEPA cannot reclaim money spent on regulating its use. Updated and strengthened regulations under the upcoming Integrated Authorisation Framework offers a flexible permitting scheme and the potential for tighter controls around breaches in compliance. In particular, SEPA is committed to promoting safe levels of contaminants in soils and sludge products as well as monitoring and auditing application procedures. The independent body Environmental Standards Scotland (ESS) has identified soil health as a key area of focus and acts as a watchdog for SEPA and regulation adherence and policy suitability. However, they will not take action unless there is clear evidence of a systemic problem in Scotland. In general, the barriers to any change in regulation of chemicals are the lack of clear evidence of harm and associated legislation from Government and the lack of a current alternative use for sewage sludge which aligns with circular economy goals. In addition, the lack of agreed methodologies for sampling and analysis to measure levels of microplastics in sludge and receiving soils are a barrier.

Protection of soil is an important driver for many stakeholders. Environmental NGOs as well as farmers and farming bodies (NFU/NFUS) are concerned about long-term soil health as well as accumulation of environmentally persistent chemicals. The health of agricultural soils for future growing and grazing is most likely to be of concern to farm land owners and may be less of a concern for tenant farmers who may be the users of biosolids fertilisers. The Scottish farming industry also relies on fertiliser availability and sewage sludge is an attractive low-cost option. As well as the soil, consideration of the crops grown in it and animals grazing on it bring in another group of stakeholders. The British Retail Consortium (BRC) are a trade association for all UK retailers and contributed to the development of the Safe Sludge Matrix.

At the individual retailer level, organic produce suppliers and many whisky producers will not use crops grown on sludge treated land. In the future, pressure to meet high standards such as these from produce retailers may further reduce the available land for sludge application.

In addition to the SUiAR, the Controlled Activities Regulations (CAR) General Binding Rules (GBRs) covering diffuse pollution also control the application of organic materials to land[24]. As with any fertiliers applied to land, it is important that the loss of nutrients to water courses and ground water is prevented.

5. Contaminants of concern in Sewage Sludge applied to land

5.1 Heavy metals

Heavy metals present in soil and sewage sludge have long been part of regulation in Scotland. Levels in sludge vary based on the nature of the influent wastewater being treated and the proportion of it that comes from industrial sources. As outlined in Section 3.1, maximum loads for key heavy metals are set within the SUiAR regulations in order to avoid risk to human health via metal uptake by plants. With scientific literature well established in this area of concern, regulators around the world generally implement similar controls and testing requirements. In the European Union, a precautionary principle is applied to limits with many member states setting their own limits well below the European Sludge Directive requirements[25]. In a 2012 European wide review, an evaluation of contaminant levels in 63 sewage sludge samples from 15 different EU countries concluded that heavy metal levels were below the limits set by current regulation[26].

In the UK, as industry has moved away from producing highly polluting industrial wastewater thanks to effective source control measures, heavy metal limits appear to be met by sludge producing sites. In the UK, Charlton et al. studied the long term effect of Zn, Cu and Cd in SS application on soil microbial biomass carbon[27]. When considering an immediate risk to humans, the limits on heavy metals were deemed sufficient to prevent a large accumulation in agricultural plants. The study did however conclude that the limits did not protect soil health in the same way. For two of the metals studied, disruption to the soil microbial community was observed at application of metal levels below the UK regulatory limits. The Chemical Investigation Program (Scotland) is also active in trying to understand the levels of heavy metals present in sludge. Sludge sampling conducted in 2019 at the Scottish Water Galashiels site found all regulated metal levels to be below the proposed limits in the revised European Commission 2011 Sludge Directive revision working document outlined in Table 1.

[24] https://www.sepa.org.uk/media/594166/sepa-materials-to-land-report-v2.pdf

[25] V. Inglezakis *et al.*, European Union legislation on sewage sludge management. *Fresenius Environmental Bulletin* **23**, 635-639 (2014).

[26] European Commission - Joint Research Centre (JRC), *EU Wide Monitoring Survey on Waste Water Treatment Plant Effluents* (2012).

[27] A. Charlton, R. Sakrabani, S. P. McGrath, C. D. Campbell, Long-term Impact of Sewage Sludge Application on biovar : An Evaluation Using Meta-Analysis. *J Environ Qual* **45**, 1572-1587 (2016).

Table 3: Thresholds relevant to sludge application to land.

	EU Sludge Directive (*10*) [mg/kg dry matter]	Working draft 2011 - revision (*11*) [mg/kg dry matter]
Cadmium	20-40	10
Chromium		1000
Copper	1000-1750	
Lead	750-1200	500
Mercury	16-25	10
Nickel	300-400	300
Zinc	2500-4000	2500

Low levels of heavy metals applied to land lead to accumulation[28] and affect long term soil health[29], despite the regulation and testing currently in place. Uptake of heavy metals by food crops presents a route to human exposure. The James Hutton Institute report noted that although accumulation of heavy metals in food crops was shown in a large number of research studies, the conditions of a laboratory based exposure experiment were not realistic to determine the risk for real world soils[30]. The report therefore did not conduct any formal risk assessment for heavy metals.

5.2 Pathogens

Domestic wastewater is a major source of pathogens to wastewater and therefore to sludge. Bacteria[31], viruses[32], protozoa[33] and prions[34] have been detected in sewage sludge, some of which pose potential health risks to humans. Despite this, UK legislation does not currently

[28] G.-h. Yang *et al.*, Accumulation and bioavailability of heavy metals in a soil-wheat/maize system with long-term sewage sludge amendments. *Journal of Integrative Agriculture* **17**, 1861-1870 (2018).
M. K. Jamali *et al.*, Heavy metal accumulation in different varieties of wheat (Triticum aestivum L.) grown in soil amended with domestic sewage sludge. *Journal of Hazardous Materials* **164**, 1386-1391 (2009).
E. M. Eid, K. H. Shaltout, Bioaccumulation and translocation of heavy metals by nine native plant species grown at a sewage sludge dump site. *International Journal of Phytoremediation* **18**, 1075-1085 (2016).
[29] A. Zaragüeta *et al.*, Effect of the Long-Term Application of Sewage Sludge to A Calcareous Soil on Its Total and Bioavailable Content in Trace Elements, and Their Transfer to the Crop. *Minerals* **11**, 356 (2021).
[30] Scottish Government, *Spreading of sewage sludge to land* (2016 https://www.gov.scot/publications/impacts-human-health-environment-arising-spreading-sewage-sludge-land-cr-2016-23-project-summary/pages/2/).
[31] A. L. Nascimento *et al.*, Sewage Sludge Microbial Structures and Relations to Their Sources, Treatments, and Chemical Attributes. *Frontiers in Microbiology* **9**, (2018).
[32] S. Gholipour *et al.*, Occurrence of viruses in sewage sludge: A systematic review. *Science of The Total Environment* **824**, 153886 (2022).
K. Bibby, J. Peccia, Identification of Viral Pathogen Diversity in Sewage Sludge by Metagenome Analysis. *Environmental Science & Technology* **47**, 1945-1951 (2013).
[33] P. Madoni, Protozoa in wastewater treatment processes: A minireview. *Italian Journal of Zoology* **78**, 3-11 (2011).
[34] G. T. Hinckley *et al.*, Persistence of pathogenic prion protein during simulated wastewater treatment processes. *Environ Sci Technol* **42**, 5254-5259 (2008).

include acceptable levels of pathogen load in sewage sludge applied to land. The voluntary Safe Sludge Matrix stipulates that sludge be treated to reduce pathogen loads before application to land. Based on the planted crop type, clear guidance is given to determine the minimum level of treatment that is acceptable in order to reduce the risk to an acceptable level. All water companies in the UK adhere to the Matrix and are certified under the Biosolids Assurance Scheme. The Safe Sludge Matrix also sets out requirements for grazing and harvest intervals and the farmer is responsible for complying with these requirements.

In order to determine the microbiological load of environmental samples, E. Coli is typically used as an indicator. The Safe Sludge Matrix uses E. Coli reduction as the indicator for quality assurance dictating that treatment of sludge destined for application to agricultural land falls below threshold limits. Some criticise this approach due to the potential to produce a false negative result for pathogen contamination if the microbiological species present (ie. Something other than E. Coli) is in a much higher concentration than the indicator organism. Furthermore, re-growth of bacteria after sludge treatment (during storage or within the soil) may also lead to levels above those expected from initial test results. Viruses, protozoa and prions are expected to be affected in varying degrees by different treatment methods[35].

An important concern in Sludge application to agricultural land is its potential to promote antimicrobial resistance[36]. Antibiotics and pharmaceuticals in wastewater and sludge applied to land can cause problems themselves (See section 5.3) but might additionally result in an increase in antibiotic resistance. Advanced sludge treatment such as anaerobic digestion or lime stabilisation reduces the viability of bacteria including those with antibiotic resistance. Despite a reduction in live bacteria, sewage sludge spreading to land may be a significant source of antibiotic resistant genes to the environment[37]. A discussion of the potential transfer of resistance within the soil environment enabled by the presence of this genetic material is available in the literature[38]. In a study by Chen et al. of the long-term impacts of sludge to land, the overall diversity of bacteria in soil increased significantly[39]. The researchers attributed this shift in bacterial community to a transfer of genetic material and genes in the environment, accelerated by the presence of sewage sludge.

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[35] EUROPEAN COMMISSION DIRECTORATE-GENERAL ENVIRONMENT, *EVALUATION OF SLUDGE TREATMENTS FOR PATHOGEN REDUCTION – FINAL REPORT* (2001 https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_eval.pdf)

[36] K. Bondarczuk, A. Markowicz, Z. Piotrowska-Seget, The urgent need for risk assessment on the antibiotic resistance spread via sewage sludge land application. *Environment International* **87**, 49-55 (2016).

[37] L. Jauregi, L. Epelde, I. Alkorta, C. Garbisu, Agricultural Soils Amended With Thermally-Dried Anaerobically-Digested Sewage Sludge Showed Increased Risk of Antibiotic Resistance Dissemination. *Frontiers in Microbiology* **12**, (2021).

[38] L. Riber *et al.*, Exploring the immediate and long-term impact on bacterial communities in soil amended with animal and urban organic waste fertilizers using pyrosequencing and screening for horizontal transfer of antibiotic resistance. *FEMS Microbiol Ecol* **90**, 206-224 (2014).

T. O. Rahube *et al.*, Impact of fertilizing with raw or anaerobically digested sewage sludge on the abundance of antibiotic-resistant coliforms, antibiotic resistance genes, and pathogenic bacteria in soil and on vegetables at harvest. *Appl Environ Microbiol* **80**, 6898-6907 (2014).

C. S. Hölzel *et al.*, Sewage sludge and liquid pig manure as possible sources of antibiotic resistant bacteria. *Environ Res* **110**, 318-326 (2010).

[39] Q. Chen *et al.*, Long-term field application of sewage sludge increases the abundance of antibiotic resistance genes in soil. *Environ Int* **92-93**, 1-10 (2016).

5.3 Organic emerging contaminants, personal care products and pharmaceuticals

The chemical contaminants present in wastewater are hugely variable depending on the nature of activities producing them. Heavily industrialised, agricultural and domestic wastewater catchment areas all produce chemical contaminants of concern.

The James Hutton Institute identified 35 organic contaminants of concern and 25 personal care products (PCPs)/pharmaceuticals present in sludge in their report prepared for the Scottish Government[40]. They selected chemicals from literature based on their presence in sludge and the availability of environmental partitioning data (specifically the partition coefficients which allow calculation of the proportion of pollutant retained in water, soil, plant matter etc.). Combining the literature data with worst-case scenario pollution levels present in the biosolids enables an estimate of the concentration of organics which may enter into food crops, water and soil.

Of the chemicals considered, the report highlights several chemicals as contaminants of key concern. These are detergents nonylphenol and nonylphenol diethoxylate (NP2EO), and the flame retardants PBDE-99 and PBDE-209. Of the PCPs/pharmaceutical contaminants investigated benzothiazole, triclocarban, cyclomethicone 5 & 6 and atenolol were deemed to carry a risk to human health via exposure in food crops. A risk via food crop exposure was also mentioned for metformin, sertraline and tamoxifen. However, the worse case magnitude of risk forall the highlighted contaminants was found to be 'low', except for benzothiazole which was medium-low. The report advises that these risks may be mitigated through use of improved biosolids treatment methods, management of cropping systems to reduce contaminant uptake into produce as well as upstream source control of contaminants.

Globally, estimates of the chemical pollution risk of sludge to land highlight similar contaminants of concern. Mejias et al. review the literature on pharmaceutical content of sludge and impacts when applied to land[41]. Concentrations are affected by anaerobic digestion and composting treatment with final concentrations diluted through mixing with soil. However, the authors highlight critical compounds triclocarban, triclosan, ciprofloxacin and 17α-ethinylestradiol carry risk even at the levels applied and call for an assessment of the distribution and risk of organics and their metabolites in soil and sludge. Verlicchi et al. discuss pharmaceuticals and personal care products in treated and untreated sludge with a focus on chemicals retained in soil after application[42]. Estradiol, ciprofloxacin, ofloxacin, tetracycline, caffeine, triclosan and triclocarban are highlighted as critical compounds in the soil and the authors again call for improved environmental risk assessment on the issue.

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[40] Scottish Government, *Spreading of sewage sludge to land* (2016 https://www.gov.scot/publications/impacts-human-health-environment-arising-spreading-sewage-sludge-land-cr-2016-23-project-summary/pages/2/).

[41] C. Mejías, J. Martín, J. L. Santos, I. Aparicio, E. Alonso, 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 (2021).

[42] P. Verlicchi, E. Zambello, Pharmaceuticals and personal care products in untreated and treated sewage sludge: Occurrence and environmental risk in the case of application on soil - A critical review. *Sci Total Environ* **538**, 750-767 (2015).

5.4 Microplastics

Microplastics are generally identified as plastic material with a diameter of less than 5 mm. They make their way into our wastewater system by many routes including domestic laundry, urban runoff and cosmetic products[43].

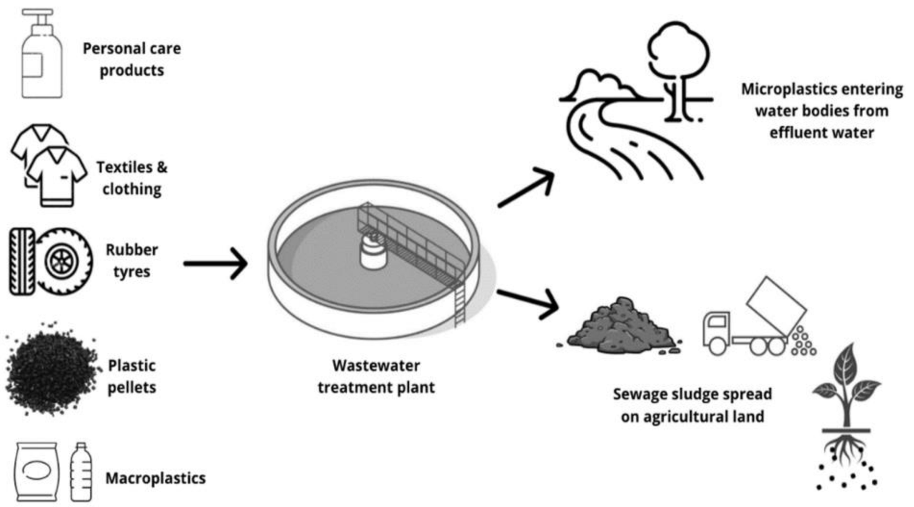

Figure 3: Microplastic prevalence in wastewater treatment systems, image courtesy of Milojevic et al.[44]

Household cleaning products can contain small beads of plastic, similarly industrial abrasion additives used in sandblasting often use small plastic pellets or fragments. Industrial plastic precursor pellets (termed nurdles) are the raw form of plastic for many industrial uses. Shedding of synthetic clothing fibres during washing cycles releases thousands of secondary microplastic fibre fragments in wastewater.

Removal of plastics from wastewater during waterwater treatment processes result in them becoming concentrated into the solid sludge phase. Up to 99% removal rates from water have been recorded for a site in Scotland[45], with similarly high proportions at sites around the world[46]. Larger fragments are separated during screening and filtration steps and smaller microplastics settle out during a sedimentation stage or captured in the sludge produced during biological digestion reactors[47].

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[43] A. Tursi *et al.*, Microplastics in aquatic systems, a comprehensive review: origination, accumulation, impact, and removal technologies. *RSC Advances* **12**, 28318-28340 (2022).
[44] N. Milojevic, A. Cydzik-Kwiatkowska, Agricultural Use of Sewage Sludge as a Threat of Microplastic (MP) Spread in the Environment and the Role of Governance. *Energies* **14**, 6293 (2021).
[45] https://www.gov.scot/publications/sewage-sludge-processing-systems-scotland/pages/2/
[46] F. Murphy, C. Ewins, F. Carbonnier, B. Quinn, Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environmental Science & Technology* **50**, 5800-5808 (2016).
O. M. Rodríguez-Narvaez, A. Goonetilleke, L. Perez, E. R. Bandala, Engineered technologies for the separation and degradation of microplastics in water: A review. *Chemical Engineering Journal* **414**, 128692 (2021).
Z. Wang, T. Lin, W. Chen, Occurrence and removal of microplastics in an advanced drinking water treatment plant (ADWTP). *Science of The Total Environment* **700**, 134520 (2020).
[47] E. Zilinskaite, M. Futter, D. Collentine, Stakeholders' Perspectives on Microplastics in Sludge Applied to Agricultural Land. *Frontiers in Sustainable Food Systems* **6**, (2022).

The actual concentration of microplastics in wastewater effluent and sewage sludge appears to be highly variable and any estimate therefore comes with significant uncertainty. Literature has estimated from 720 – 14,900 particles per kg (wet weight) and 1000 – 170,900 particles per kg (dry weight) in sewage sludge[48]. In part, this is due to fluctuations in the microplastic load of wastewater entering the treatment site but also challenges in measuring microplastic concentrations[49]. The type of wastewater treatment applied also affects the proportion of microplastics removed from water as reviewed by Iyare et al[50]. Their meta-analysis indicated that the initial primary treatment steps of skimming and sedimentation removed the majority of plastics from the water (around 72%). The settling velocity of the particles in water allowed them to conclude that during this stage, larger particles are preferentially removed meaning sewage sludge is likely to contain high proportions of the largest fraction. This is in agreement with a study that observed contents of sludge from a treatment works in Glasgow contained a high proportion of large microplastics when compared to the effluent water[51]. Of 15,000 microplastics per cubic meter estimated to enter into a Swedish treatment plant (12,000 population equivalent in size), more than 99% were captured in the sewage sludge[52].

When scaled up, this level of pollution means that huge numbers of microplastics are present in the sludge applied to agricultural land. For the EU, assuming an approximate generation of 10 million tonnes of sludge annually, a range of $7.2 \times 10^{12} – 1.49 \times 10^{14}$ (7.2 - 149 trillion) plastic particles pervades it[53]. Sludge has been named a prime driver of soil plastic pollution by researchers[54].

A. A. Horton *et al.*, Semi-automated analysis of microplastics in complex wastewater samples. *Environmental Pollution* **268**, 115841 (2021).
S. S. Alavian Petroody, S. H. Hashemi, C. A. M. van Gestel, Transport and accumulation of microplastics through wastewater treatment sludge processes. *Chemosphere* **278**, 130471 (2021).
P. U. Iyare, S. K. Ouki, T. Bond, Microplastics removal in wastewater treatment plants: a critical review. *Environmental Science: Water Research & Technology*, (2020).
M. R. Michielssen, E. R. Michielssen, J. Ni, M. B. Duhaime, Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed. *Environmental Science: Water Research & Technology* **2**, 1064-1073 (2016).
[48] P. U. Iyare, S. K. Ouki, T. Bond, Microplastics removal in wastewater treatment plants: a critical review. *Environmental Science: Water Research & Technology*, (2020).
[49] M. S. M. Al-Azzawi *et al.*, Microplastic sampling from wastewater treatment plant effluents: Best-practices and synergies between thermoanalytical and spectroscopic analysis. *Water Research* **219**, 118549 (2022).
W. Fu, J. Min, W. Jiang, Y. Li, W. Zhang, Separation, characterization and identification of microplastics and nanoplastics in the environment. *Science of The Total Environment* **721**, 137561 (2020).
R. C. Hale, Analytical challenges associated with the determination of microplastics in the environment. *Analytical Methods* **9**, 1326-1327 (2017).
[50] P. U. Iyare, S. K. Ouki, T. Bond, Microplastics removal in wastewater treatment plants: a critical review. *Environmental Science: Water Research & Technology*, (2020).
[51] F. Murphy, C. Ewins, F. Carbonnier, B. Quinn, Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environmental Science & Technology* **50**, 5800-5808 (2016).
[52] K. W. Magnusson, C., "Screening of Microplastic Particles in and Down- Stream of a Wastewater Treatment Plant.," (Swedish Environmental Research Institute, Stockholm, Sweden, 2014).
[53] P. U. Iyare, S. K. Ouki, T. Bond, Microplastics removal in wastewater treatment plants: a critical review. *Environmental Science: Water Research & Technology*, (2020)
[54] F. Corradini *et al.*, Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Science of The Total Environment* **671**, 411-420 (2019).

Despite the clear evidence of pollutant presence, identifying risk thresholds is a challenge when considering microplastic pollution. The body of literature on environmental risk, although developing, is yet to define a safe level of exposure in soil. Without a defined acceptable safe level, it is impossible for regulators to set limits for microplastics in environmental media.

6. Impacts on soil quality

Sewage sludge has a high content of organic matter and biogenic elements (carbon, nitrogen, phosphorus), which are essential for plant growth and development as well as soil microbiota health. Sewage sludge application to land is a useful way of ensuring elements are recycled and provides a cheap source of fertiliser. The rate of application to agricultural land is important in preventing excessive nutrient loads entering the soil or causing runoff to waterways and is controlled in Scotland by the SUiAR, Ntirate Regulations and the CARegs, summarised and supplimented by best practice in the Biosolids Assurance Scheme as discussed in Section 3.1.

Dry sludge typically contains 50-70% organic matter and 30-50% mineral components, although this is highly variable depending on the nature of the wastewater and treatment system the sludge is derived from[55]. Soils amended with sewage sludge have shown improved soil structure, nutrient storage, improved porosity and water retention[56].

The nutrient content of biosolids depends largely on the treatment process with thermally dried sludge providing the largest proportion of nitrogen, phosphorus, potassium, sulfur and magnesium (in line with providing the highest dry matter content)[57]. In Scotland, much of the sludge applied to land undergoes advanced anaerobic digestion producing solid material with a relatively low proportion of nutrients by mass. On a dry weight basis, biosolids contain between 1-11% nitrogen and 0.7-7.5% phosphorus while commercial chemical fertilisers can range 15-82% nitrogen and 8-76% phosphorus[58]. Low concentrations may provide an advantage over chemical fertiliser in the slow release of nutrients to soil over time. The large range in availability of nutrients is likely due to varying soil conditions such as pH, biosolids origin/source materials and method of measurement[59]. A full breakdown of the available

[55] A. Fließbach, R. Martens, H. H. Reber, Soil microbial biomass and microbial activity in soils treated with heavy metal contaminated sewage sludge. *Soil Biology and Biochemistry* **26**, 1201-1205 (1994).
[56] E. Picariello *et al.*, Compost and Sewage Sludge for the Improvement of Soil Chemical and Biological Quality of Mediterranean Agroecosystems. *Sustainability* **13**, 26 (2021).
E. M. Eid *et al.*, The evaluation of sewage sludge application as a fertilizer for broad bean (Faba sativa Bernh.) crops. *Food and Energy Security* **7**, e00142 (2018).
[57] "Optimising the application of bulky organic fertilisers," (Scotland's Rural College, Edinburgh, 2013).
[58] K. R. Kim, G. Owens, in *Comprehensive Biotechnology (Second Edition),* M. Moo-Young, Ed. (Academic Press, Burlington, 2011), pp. 239-247.
S. Spicer, Fertilizers, manure; or biosolids? *Water Environment and Technology* **14**, 32-35 (2002).
[59] S. Nanzer *et al.*, The plant availability of phosphorus from thermo-chemically treated sewage sludge ashes as studied by 33P labeling techniques. *Plant and Soil* **377**, 439-456 (2014).
S. O. Petersen, J. Petersen, G. H. Rubæk, Dynamics and plant uptake of nitrogen and phosphorus in soil amended with sewage sludge. *Applied Soil Ecology* **24**, 187-195 (2003).

nutrient loads of biosolids is available in Table 4 (taken from a technical note prepared by SRUC)[60].

Table 4. Typical dry matter (DM) and nutrient contents of treated liquid and solid biosolids, produced using different treatment methods (taken from SRUC Optimising the application of bulky organic fertilisers technical note[57])

Manure type	DM (%)	kg/t (solid manures) or kg/m^3 (liquids/slurries)					
		Total N	Readily available N	Total P_2O_5	Total K_2O	Total SO_3	Total MgO
Biosolids, liquid digested	4	2.0	0.8	3.0	0.1	1.0	0.3
Biosolids, digested cake	25	11	1.6	18	0.6	6.0	1.6
Biosolids, thermally dried	95	40	2.0	70	2.0	23	6.0
Biosolids, thermally hydrolysed	30	10	1.0	20	0.5	7.5	1.5
Biosolids, lime stabilised	40	8.5	0.9	26	0.8	8.5	2.4
Biosolids, composted	60	11	0.6	6.0	3.0	2.6	2.0

Sewage sludge increases the microbial biomass and diversity in the soil. This can have implications beyond those for antibiotic resistance already discussed in Section 5.2. Increased microbial biomass competes with crops for phosphorus uptake. The phosphorus delivered within sewage sludge is contained in a less readily available form than that found in chemical fertilisers, meaning its delivery to plants is slower[61]. With increased competition from bacteria for nutrients, the actual benefit to plants is likely to be significantly lower than initially indicated by nutrient loads delivered.

Sewage sludge can provide a useful cheap fertiliser which despite having some drawbacks in terms of element delivery and availability, can improve the soil's ability to promote plant growth. One main drawback in terms of soil quality is the long-term sink of persistent pollutants such as microplastics and organic chemicals. Limited information is available as to the fate and transfer of many of these chemicals but due to their longevity in natural systems, it can be expected that continued long-term application to land will result in an accumulation. Another potential drawback for soil quality from using sewage sludge over long time periods is nutrient imbalances, which, if not corrected, can become a major issue. Biosolids contain high levels of phosphorus but low levels of potassium, which can lead to phosphorus accumulation and potassium decline in soils if they are used as a primary source of fertiliser. In extreme cases, this can lead to yield reductions as well as wider environmental risk from phosphate enrichment. Regular soil nutrient testing is important for maintaining healthy productive soils.

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[60] SRUC, *Optimising the application of bulky organic fertilisers* (2013 https://www.farmingandwaterscotland.org/downloads/sac-technical-note-tn650-optimising-the-application-of-bulky-organic-fertilisers/).

[61] A. Andriamananjara, L. Rabeharisoa, L. Prud'homme, C. Morel, Drivers of Plant-Availability of Phosphorus from Thermally Conditioned Sewage Sludge as Assessed by Isotopic Labeling. *Frontiers in Nutrition* **3**, (2016).

7. Circular economy considerations

Application of treated sludge to land was introduced as an alternative to disposal at sea or landfill with circular economy benefits in mind. Any proposal seeking to change this practice must consider carefully the sustainability implications.

Many sludge treatment and energy-from-waste processing methods are energy intensive (incineration, pyrolysis, nutrient recovery before or after pyrolysis) and require significant infrastructure overhaul to be viable options in Scotland. Direct disposal options generally are not in line with sustainability goals. The final ash produced by incineration holds high levels of contaminants and flue gas produced during the process is environmentally harmful. Nutrient recovery, although process intensive, may offer a solution that recovers the valuable mineral content of sludge. After nutrient and metal extraction, the remaining residual material is a heavily contaminated waste with no viable use and is usually incinerated or pyrolysed. Pyrolysis has the potential to produce a useful biochar by-product at a lower operating temperature than incineration and this biochar can be used in construction or as a soil amendment.

Farmers using sewage sludge as a fertiliser do so as a cheap source of nutrients. The most common alternative to sludge fertiliser is to use mined phosphorus and other chemical based fertilisers which are damaging to the environment, particularly in terms of greenhouse gas (GHG) emission during their production[62], although it should be noted that GHG emissions and potential nutrient losses are associated with all fertiliser application and storage activities. In a recent article from Food Manufacture, the importance of fertiliser availability to Scottish food security was laid clear[63]. A 200% increase in fertiliser costs presents a key challenge for growers in 2023. Some farming communities call for the government to ensure farmers can make efficient use of nutrient sources and sewage sludge offers some benefit in this context. However, the actual number of farmers relying on sludge for fertiliser in Scotland is low.

8. Conclusions and key recommendations

Application of sewage sludge to agricultural land introduces organic chemical and microplastic pollution to Scottish soils. It should be noted that this happens in the context of application of other organic materials to agricultural land which are also a potential source of contaminants. There is no monitoring system in place for levels for these contaminants in sewage sludge and a limited understanding of the potential risk to health from human exposure or bioaccumulation impact. For microplastics there is no agreed methodology for sampling and analysis. Priority must be given to preventing these contaminants entering the waste water system, for example through further bans on the use of microplastics, requiring washing machines to be fitted with filters and banning the use of PFAS[64]. However, given the

[62] S. Wood, A. Cowie, *A Review of Greenhouse Gas Emission Factors for Fertiliser Production*. (2004), vol. 38, pp. 20.
[63] B. Grylls. (Food Manufacture, 2022), vol. 2023.
[64] Fidra. (2023).

sources are many and varied, it is also essential that the regulation of sewage sludge and its application is also improved.

Upcoming changes to the way sewage sludge regulation is managed under the Integrated Authorisation Framework offers improvement over the complex combination of regulatory schemes currently in place and could lead to limits on emerging contaminants, if supported by evidence. Sewage sludge to land is a complex area with numerous stakeholders across the water, farming, waste and energy sectors. Policymakers should consider the risks alongside the benefits in terms of nutrient recycling that the practice offers. While the benefits of sludge recycling over disposal are clear, it must be achieved in a safe and environmentally friendly way to align with the circular economy goals and the human right to a healthy environment as set out by the Scottish Government.

In response to the consultation on the implementation of the IAF, attention should be drawn to the numerous issues associated with application of sewage sludge to land in Scotland. An overhaul of the complex and outdated legislation on this issue is welcome but in order to protect soils and the health of our environment, the Scottish Government must take further action:

- Incorporation of existing voluntary schemes (Biosolids assurance scheme and Safe Sludge Matrix) into law to ensure all sludge produced in Scotland destined for agricultural land meets minimum quality levels.
- Regulatory bodies should be given increased power to audit and enforce compliance with contaminant levels of sludge and soils, to increase confidence in the current safety of sludge use as well as providing a potential value recovery mechanism to regulators via permitting costs.
- Based on the evidence provided in Scottish Government Commissioned reports, monitoring of key chemical contaminants should be carried out in soils and sludge to determine the level of long term risk posed by emerging contaminants.
- based on this testing, maximum safe levels for emerging contaminants and microplastics may be established which would allow regulations on maximum levels to be defined.
- Alternatives to sludge spreading to agricultural land should be explored and prioritised if the level of risk cannot be defined based on current knowledge.

By Thomas Easton
Institute of Infrastructure and Environment
School of Engineering | University of Edinburgh

M. C. Society, "Sewage sludge: Why we need to stop pollution at source," (2021).