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CHARACTERISATION OF NEW ZEALAND DIGESTATE FOR CONTAMINATION RISK AND SAFE USE

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GLOSSARY OF TERMS

AD	Anaerobic digestion
BANZ	Bioenergy Association of New Zealand
BDL	Below detection limit
BPW	Buffered peptone water
CFU/g	Colony-forming units per gram
CM1 / CM2	Ontario categories for non-agricultural source materials under Ontario Regulation 267/03
DBPAS	Digestate Biofertilizer Producer Accreditation Scheme
FTIR	Fourier-transform infrared spectroscopy
HF	Hydrofluoric acid
ICP-MS	Inductively coupled plasma mass spectrometry
LC-MS/MS	Liquid chromatography tandem mass spectrometry
MAC	MacConkey agar
N, P, K	Nitrogen, phosphorus, potassium
NASM	Non-agricultural source material
PFAS	Per- and polyfluoroalkyl substances
PFCA	Perfluoroalkyl carboxylic acid
PFSA	Perfluoroalkyl sulfonic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
PFBA	Perfluorobutanoic acid
PFBS	Perfluorobutane sulfonate
PP / PE / PET	Polypropylene / polyethylene / polyethylene terephthalate
TOP assay	Total oxidisable precursor assay
TSA	Tryptic soy agar
XLD	Xylose lysine deoxycholate agar
$ZnCl_2$	Zinc chloride

EXECUTIVE SUMMARY

Anaerobic digestion is becoming increasingly important in New Zealand as a way to manage organic wastes while recovering value through biogas and digestate. Digestate has clear potential to be used as a biofertiliser or soil amendment, but its beneficial use depends on more than nutrient content alone. Its suitability for land application is shaped by feedstock source, contaminant profile, treatment performance, and the strength of the evidence used to assess risk. For BANZ, digestate producers, regulators, and end users, this creates a practical need for New Zealand-based data that can support more informed decisions on digestate quality, monitoring, and future guidance.

This report addresses that need by assessing digestate from four feedstocks relevant to the New Zealand anaerobic digestion sector: food waste, dairy waste, manure waste, and sewage sludge. These digestates were compared with soil, compost, and synthetic fertiliser reference samples to place the results in a more practical context. The project combined literature review, laboratory analysis, and interpretation against selected international screening benchmarks to examine nutrients, metals, pathogens, PFAS, and plastics/microplastics. The purpose was not to treat digestate as a single generic product, but to understand how quality varies between feedstocks and what that means for beneficial use, monitoring, and regulatory development.

The results show clearly that digestate quality is feedstock-dependent. Nutrient concentrations varied substantially across digestate types, confirming that digestate can provide agronomic value, but also showing that nutrient content and likely application value differ between feedstocks. The contaminant results were similarly variable. PFAS analysis showed that targeted LC-MS/MS alone did not capture the full PFAS picture, with TOP assay indicating likely oxidisable precursor burden and a strong post-oxidation pattern dominated by short-chain PFAS. Metals analysis showed that most regulated metals were generally below the screening limits used for comparison, but manure digestate stood out for elevated zinc and copper, while sewage-derived digestate showed the highest overall background metal burden. Microbiological screening indicated strong presumptive *E. coli*-type counts in dairy and sewage digestates, while presumptive *Salmonella*-type colonies were not observed in the digestate samples under the test conditions used. Microplastics analysis did not provide clear confirmation of microplastic presence, highlighting methodological uncertainty rather than evidence of absence.

A key finding of the project is that regulatory coverage remains uneven. Traditional contaminants such as metals and pathogens are comparatively better addressed in international frameworks, although digestate-specific limits remain limited and many available benchmarks relate instead to biosolids, compost, or other product classes. For emerging contaminants, especially PFAS and microplastics, the regulatory gap is much greater. As a result, international values should be treated as screening references and decision-support tools rather than as direct compliance standards for digestate in all cases.

Overall, this project provides an important early evidence base for BANZ and its stakeholders. Its central message is clear: digestate should not be viewed as a single uniform biofertiliser product. Some digestates show strong potential for beneficial use, but safe and confident land application requires feedstock-aware assessment, targeted monitoring, stronger source control, improved methods for emerging contaminants, and the gradual development of clearer digestate-specific guidance for New Zealand.

1. INTRODUCTION

1. INTRODUCTION

Anaerobic digestion is becoming increasingly important in New Zealand as a way to manage organic wastes while recovering value through biogas and digestate. Digestate has the potential to be used as a biofertiliser or soil amendment, supporting nutrient recycling and reducing reliance on synthetic fertilisers. However, the quality of digestate is not uniform. It can vary significantly depending on the feedstock, upstream contamination sources, and processing conditions used in the anaerobic digestion system. For industry, this creates an important question: under what conditions can digestate be used safely and confidently on land?

This report was prepared to help address that question. Its purpose is to provide BANZ and its stakeholders with a practical evidence base on digestate quality across selected New Zealand-relevant feedstocks. The focus is not only on nutrient value, but also on potential contaminants that may influence product quality, market confidence, monitoring needs, and future regulatory development. The study considers both beneficial components and potential risks. Nutrients such as nitrogen (N), phosphorus (P), and potassium (K) are important for plant growth and are central to the value of digestate as a recovered product. At the same time, contaminants such as metals, pathogens, PFAS, and plastics/microplastics may affect the suitability of digestate for land application and may require additional monitoring, management, or policy attention. Traditional contaminants such as metals and pathogens are already addressed to some extent in international frameworks, whereas emerging contaminants such as PFAS and microplastics remain less well defined in digestate-specific guidance.

In New Zealand, interest in digestate use is increasing, but there is still limited comparative information on digestate composition across different feedstocks and limited digestate-specific guidance for some contaminants, particularly emerging ones. This creates uncertainty for producers, end users, and regulators. A clearer understanding of digestate quality is therefore needed to support good practice, informed decision-making, and future development of monitoring and regulatory approaches.

1.1. Aim

The overall aim of this project was to assess the quality of digestate from selected feedstocks relevant to New Zealand and to provide practical guidance on its beneficial use, monitoring, and regulatory considerations.

1.2. Objectives

The specific objectives were to:

- review current knowledge on digestate quality, including nutrients, metals, pathogens, PFAS, and plastics/microplastics
- analyse and compare digestate samples from different feedstocks relevant to New Zealand
- compare digestate results with selected reference materials, including soil, compost, and synthetic fertiliser

- interpret the findings against relevant international benchmarks and regulatory frameworks where available
- identify key data gaps, methodological limitations, and priorities for future monitoring and policy development

1.3. Scope of the Report

This report brings together the three phases of the project.

- Phase 1 reviewed the literature on digestate quality, contaminant risks, analytical methods, and relevant New Zealand and international frameworks.
- Phase 2 involved laboratory analysis of digestate and reference samples to characterise nutrients and selected contaminants.
- Phase 3 interprets the findings and provides recommendations for monitoring, methodology, and regulatory development.

The digestate samples assessed in this study represent four feedstock types relevant to the New Zealand context: food waste, dairy waste, manure waste, and sewage sludge. These were selected to reflect different source materials and therefore different possible nutrient and contaminant profiles. Reference samples of soil, compost, and fertiliser were included to provide context for interpreting the digestate results.

The findings in this report are intended to support BANZ, digestate producers, industry stakeholders, and other interested parties in better understanding digestate quality and the key considerations for its safe and beneficial use. Comparisons with international regulations are included as screening and contextual references, rather than as direct statements of regulatory compliance, because digestate classification, product definitions, and analytical methods differ between jurisdictions.

2. Literature Review

2. LITERATURE REVIEW

The annual worldwide production of various types of waste, such as agricultural residues, animal manure, food waste, and sewage sludge, is 2, 1.3, 120, and 16.4 billion tons/year, respectively [1]. Anaerobic digestion (AD) is a widely used process for treating organic waste, offering both energy and nutrient recovery benefits. It has been used to treat a variety of waste streams, including food waste, sewage sludge, agricultural waste, and animal waste. Due to the large volume of waste generated globally, AD has become an important process for converting organic waste into biogas and digestate [2–4].

Anaerobic digestion generates digestate, a nutrient-rich by-product that can be used as a biofertilizer contributing to sustainable practices and the circular economy by improving waste management and nutrient cycling [5]. However, the variability of digestate and the significant inputs of waste streams also increase the risk of contamination in the resulting digestate, raising concerns about the safety of digestate land application. Digestate quality can vary significantly depending on feedstock composition and operational AD conditions, which influence nutrient content and the presence of potential contaminants [6, 7].

With the global increase in digestate application, particularly in agriculture, there is growing concern regarding contaminants such as per- and polyfluoroalkyl substances (PFAS), microplastics, and heavy metals. These substances persist in the environment and may transfer to the soil, posing risks to soil and human health, food safety, and environmental ecosystems [8]. Furthermore, current regulations and monitoring frameworks are limited and fail to address these emerging contaminants adequately. The lack of standardised limits, especially for PFAS and microplastics, makes it challenging to assess their concentrations and long-term implications [9].

With the increasing use of digestate and its potential to contaminate agricultural land, there is a need to understand better the risks associated with its use. This review aims to establish a foundation of existing knowledge on the use of digestate and its safety by examining its exposure pathways to PFAS, microplastics, and heavy metals. Additionally, it evaluates methodologies for testing contaminants in environmental matrices that can be applied to digestate and examines existing regulations. The review also highlights knowledge gaps to support more consistent monitoring and evidence-based policies for the safe use of land-applied digestate.

2.1. Digestate

2.1.1. Formation of Digestate in AD

The AD process typically consists of four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In hydrolysis, organic matter is broken down into smaller molecules for subsequent microbial digestion. Hydrolytic bacteria convert carbohydrates, lipids, and proteins into sugars, long-chain fatty acids (LFCAs), and amino acids, respectively, by secreting enzymes [10]. In the acidogenesis stage, hydrolysed macromolecules produced in the previous stage are fermented by acidogenic bacteria, turning them into volatile fatty acids (VFAs) [11]. Acetic acid is produced in the third stage by converting other produced higher VFAs, and, at last, during the methanogenesis stage, biogas is produced [10]. While hydrolysis is often considered the rate-limiting step for

complex substrates, more readily biodegradable feedstocks (e.g., food waste) may shift the rate limitation to methanogenesis [12]. This implies that optimising the digestion process requires targeted approaches based on feedstock, waste type, and available resources to improve efficiency [13]. However, the extent to which organic material is broken down directly influences digestate quality. Poor hydrolysis may result in digestate with a greater amount of undegraded material, reducing its stability and fertiliser value [14].

The indigestible material remaining after microbial activity during AD forms digestate, which contains liquid and solid fractions. The liquid portion typically contains 2-6% dry matter in wet digesters and over 15% in dry digesters, and can be spread uniformly onto land to deliver nutrients [15, 16]. In contrast, the solid fraction comprises fibrous materials, such as lignocellulosic materials, which do not degrade through microbial activity during the AD process. Solid-liquid separation is commonly performed prior to further treatment of digestate to reduce its volume for easier handling and to enable nutrient management between the solid and liquid fractions for their respective usage. Thickening methods, such as gravity settling, filtration, air flotation, or centrifugation, are used to concentrate digestate to 5-10% suspended solids. While these techniques are typically energy-efficient, they yield a relatively dilute output. In contrast, dewatering methods such as screw presses or decanter centrifuges, which are also solid-liquid separation techniques, can concentrate digestate slurries to up to 35% solids; however, they are more expensive and energy-intensive than thickening [17]. While both methods reduce water content, their efficiency and suitability for processing digestate can vary depending on the digestate characteristics [16].

In typical wet biogas plants, the digestate mass is close to the feedstock mass, and, depending on the feedstock composition, solids content, and process efficiency, 20-95% of the feedstock organic matter (OM) is degraded [5, 18]. Unlike biosolids and compost, digestate is the by-product of AD, whereas biosolids are the treated product from wastewater plants, and compost is the product gained through the decomposition of organic matter under aerobic conditions. This distinction is important when considering regulatory classification and potential contamination risks.

2.1.2. Operational Conditions and Parameters

AD operates under several key operational conditions and parameters that affect the efficiency and stability of the process and the final product quality. Table 1 compares key parameters reported across different studies.

Temperature is a critical factor in AD, driving microbial activity, kinetic rates, and metabolic pathways, with mesophilic and thermophilic organisms being the most common in industrial-scale AD applications [19, 23]. Most anaerobic digesters operate at mesophilic temperatures due to greater stability, lower design complexity, and reduced sensitivity to toxic inhibitors [24]. However, thermophilic digestion has attracted growing interest recently since higher operating temperatures lead to higher reaction rates, thereby increasing organic matter degradation, reducing volatile solids in digestate, and improving sanitation by eliminating pathogens [10, 25]. This improved sanitation enhances the hygiene of digestate, potentially reducing the need for post-treatment. However, thermophilic conditions present several drawbacks, including increased ammonia volatilisation,

which can alter nitrogen content in the digestate; unpleasant odour; poor digestate dewaterability; higher energy and heating demands; and greater process sensitivity to changes [26, 27].

Table 1: AD parameters and their effect on digestate quality

Parameter	Range	Effect on digestate	Ref.
Temperature	Psychrophilic: 4-25°C	Psychrophilic conditions are associated with poor sanitation and produce digestate with a higher pathogen load.	[10, 19]
	Mesophilic: 30-40°C	Mesophilic retains more nitrogen, producing more nutrient-rich digestate, but may contain more pathogens.	
	Thermophilic: 50-60°C	Thermophilic provides better sanitation and degradation, but greater ammonia loss, which reduces the nitrogen fertiliser value.	
	Extremophilic: >60°C	Extremophilic provides greater degradation and high sanitation, reducing odours.	
pH	Hydrolysis and acidogenesis: ~ 5.5-6.5 Methanogenesis: ~ 6.8-7.2	Suboptimal pH results in incomplete degradation and accumulation of organic acids, producing an unstable, odorous digestate with low fertiliser value. Extreme pH alters nutrient speciation, thereby affecting digestate nitrogen availability.	[20, 21]
Hydraulic/solid Retention time (HRT/SRT)	Feedstock dependent	Longer retention times improve digestate stability and enable more complete degradation of organic matter, thereby reducing residual VFAs, pathogens, and odours. However, excessively long retention times can lead to nutrient losses through nitrogen volatilisation.	[20]
C:N ratio	20-30 optimal, but depends on the feedstock	Low C:N results in greater ammonia content due to excess nitrogen, which can reduce digestate fertiliser value through nitrogen volatilisation, creating environmental risks relating to ammonia emissions and crop safety.	[20]
Organic load rate (OLR)	Variable 0 to 8.3 gVS/L/d	Excessive OLR can cause VFA accumulation and incomplete degradation, leading to unstable digestate with reduced fertiliser value.	[10, 22]
Mixing	Variable	Well-mixed digestate is more stable and homogenised, with nutrients uniformly distributed, reduced sedimentation, and prevented VFA accumulation.	[20]

pH is a critical parameter in AD, and the optimal range varies by stage and for the production of VFAs and other organic matter. The optimal pH range for methanogenesis is 6.8-7.2, although for the overall process, 5.5-8.0 will support the microbial community [28]. A pH that is too low or too high will affect the quality of the digestate. The optimal pH varies slightly at each stage of the AD process; however, studies agree that even minor pH variations of 0.5 can significantly alter microbial metabolism, influencing reaction kinetics and, in turn, the quality of digestate [20].

Retention time is the average time organic matter spends in the anaerobic digester to achieve maximum digestion. Short retention times are more cost-efficient, but may result in unstable digestate, especially if the feedstock is high in lignocellulosic material, whereas longer retention times improve digestate stability and biofertilizer value [29]. Hydraulic retention time (HRT) refers to the time the liquid fraction spends in the digester, whereas solid retention time (SRT) is the time the solids and microorganisms are retained in the digester [30]. When feedstock and microbial cultures are in the same phase, the HRT and SRT are equal, as in food waste and municipal solid waste. In contrast, for feedstocks such as primary and waste-activated sludge, the HRT and SRT values will differ [31].

The carbon-to-nitrogen (C:N) ratio affects digestate stability by balancing microbial nutrient requirements [32]. Nitrogen is required to enable the growth of microorganisms for their specific reaction, and carbon is required as an energy source. Low C:N leads to excess ammonia, which reduces digestate value through volatilisation and poses toxicity risks to crops, while low nitrogen levels inhibit microbial community growth, keeping their population small [4, 33].

The organic loading rate (OLR) is the amount of organic material continuously fed into the digester per unit of time. While a high OLR (>7 gVS/L/D) is preferred for complete degradation, an OLR that is too high may overload the system, leading to overaccumulation of VFAs and ammonia, a pH drop, and potential system failure [22, 34]. The optimal OLR, therefore, varies and is tailored depending on individual systems.

Mixing and stirring also directly affect microorganism activity by providing uniform substrate-microorganism contact. Continuous mixing and stirring enable substrates to be in direct contact with microorganisms, reduce sedimentation, and promote uniform temperature in the digester [20]. Proper agitation can boost the biogas production up to 70% compared to unmixed systems [35, 36].

Anaerobic digesters vary in design and parameters, hence affecting the digestate produced. Digestate quality varies widely and is highly dependent on system type and configuration. The feedstock composition primarily influences the quality, the operational parameters of the AD process, and pre- and post-treatment methods, which determine the suitability as a fertiliser. Key factors include nutrient load, contaminants (heavy metals, microplastics, PFAS, and other emerging contaminants), pathogen levels, stability, and pH.

2.1.3. Feedstock Influence on Digestate Quality

While an effective AD process can enhance digestate quality, it may not eliminate potential contaminants, as digestate quality is also influenced by the composition of feedstock supplied to the process. High-quality digestate suitable for use as biofertiliser is characterised by essential features such as nutrient content, pH, and organic matter content [16]. The nutrient content of digestate varies depending on the type of feedstock, but it typically contains nitrogen, phosphorus, potassium, and other organic matter [21]. Since the AD process does not degrade all potential contaminants supplied by the feedstock, obtaining high-quality digestate depends on using feedstocks with minimal unwanted impurities [26].

Digestate from agricultural and food processing feedstocks is generally of high quality and can be safely used as fertiliser [37]. The digestate derived from food waste tends to produce more nitrogen than digestate from animal manure; however, the high nitrogen content and pH of food waste leads to greater ammonia volatilisation under seasonal conditions. This suggests that a high nitrogen content does not necessarily indicate better fertiliser value, as ammonia losses can cause greater environmental harm [38]. In addition, since crops contain lignocellulosic material and are resistant to biodegradation, the digestate produced has a higher solid content and residual nutrients, which can be helpful as soil conditioners [39].

Anaerobic digestates derived from various organic feedstocks, including animal manure, food waste, municipal solid waste, sewage sludge, and green waste, vary significantly depending on the source material. While animal manure provides a stable environment for microbial activity, lower gas yields, food waste and sewage sludge offer higher methane potential and nitrogen content, albeit with risks of high salinity or heavy metal contamination. Green waste and municipal solids provide structural benefits to soil but can be hindered by slowly decomposing lignocellulose and physical impurities. Table 2 lists the key nutrients, advantages and limitations of the most common AD feedstocks.

To overcome individual feedstock limitations such as suboptimal C:N ratios, high ammonia levels, or pathogen persistence, different approaches have been practised, with feedstock pretreatment and co-digestion being the two most common.

Table 2: Comparison of Digestate Feedstocks

Feedstock	Key Nutrients	Advantages	Common Limitations
Animal Manure	- Nitrogen (N) - Phosphorus (P)	- High buffer capacity - Contains essential microbes	- Lower gas yield - Potential presence of pathogens and antibiotics
Food Waste	- High NH_4-N - Fats - Proteins	- Excellent methane potential - Highly biodegradable	- High salt content - Plastic/physical impurities
Municipal Solid Waste	- Macro and Micronutrients	- Readily available in urban areas	- Variable composition - High risk of metal, glass, and plastic debris
Sewage Sludge	- Nitrogen (N) - Phosphorus (P) - Sulphur (S)	- High organic matter - Good micronutrient profile	- Heavy metals and persistent pharmaceutical pollutants
Green Waste	- Carbon (C) - Potassium (K)	- High fibre acts as a soil conditioner	- Slow decomposition (high lignin) - Low nitrogen content

2.1.4. Pretreatment, Recirculation and Co-digestion

Co-digestion, the strategic mixing of different waste streams, is frequently employed to enhance biogas production efficiency, create a more balanced, sustainable soil amendment, and improve stability, especially during long-term digestion [5]. It also improves nutrient balance, reduces contaminant concentration, and enhances stability [40, 41]. This synergy effect is highly dependent on the co-substrate ratios and their nature. Co-digestion of food waste with animal manures is one of the most widely practised approaches, and it has been shown to improve biogas yield and balance nutrient profiles, potentially mitigating nitrogen losses while enhancing methane production [42].

Co-digestion can also help when diluting feedstock, such as dairy sludge, to improve bacterial digestion [43]. Additionally, prior research indicated that digestate recirculation in a two-stage system can reduce chemical use and improve substrate conversion. This improvement results from reviving fermentation bacteria, which prevents VFA formation and, consequently, reduces the amount of chemicals required to maintain ideal pH levels [44].

Digestate only finds a market when it is contaminant-free, safe for the environment, and hygienic. Using clean, unpolluted co-substrates is the best and most cost-effective strategy, but it is not always possible. Feedstocks may contain physical impurities, such as indigestible material or large particles of digestible material. These impurities can be removed by pre-screening the feedstock using physical barriers. In addition, Pathogenic microbes may also be present in feedstocks, which are typically removed during mesophilic and thermophilic digestion; however, additional sanitation may be required. Pre-treatment methods such as pasteurisation, UV light, and chlorine treatment can be used to reduce pathogens in the final digestate [16]. Pretreatment approaches are categorised into three main categories: physical, chemical, and biological, with preference given to technologies that do not require chemical or enzyme addition. Their non-chemical nature reduces the risk of secondary contaminations, maintaining the digestate quality for further applications [41].

2.2. Contaminants in Digestate

Investigating the presence of contaminants of emerging concern (CECs) in digestate is critical because these substances, ranging from pharmaceuticals and microplastics to PFAS, often bypass conventional wastewater treatment processes and accumulate in the digestate, whether in the solid or liquid part. Once in the soil, these contaminants can leach into groundwater or be taken up by crops, potentially leading to long-term ecological toxicity and unforeseen risks to human health. Furthermore, the presence of these contaminants can fundamentally disrupt the biological efficiency of the anaerobic digestion process itself. High concentrations of antibiotics or synthetic chemicals can inhibit the microbial activity responsible for methanogenesis, leading to reduced biogas yields and system instability. A wide range of CECs has been identified in the digestate. In a recent study, 133 different CECs, including pharmaceuticals and personal care products (PPCPs), pesticides, and industrial chemicals, were detected [45]. Understanding these pollutants goes beyond meeting regulatory requirements; it is a necessary step to ensure that renewable energy production does not come at the cost of environmental pollution.

2.2.1. Per- and Polyfluoroalkyl Substances (PFAS)

PFAS are a large group of fully synthetic organic compounds whose environmental ubiquity has raised increasing concern due to their resistance to degradation in various waste streams, including AD. The simultaneous hydrophobic and hydrophilic nature of PFAS makes them highly stable and difficult to degrade in the environment, and they persist through AD, accumulating in the digestate [46]. The chemical structure of most PFAS types includes a charged functional group, such as a carboxylic or sulfonic acid, attached to one end of the PFAS chain. PFAS are distinguished based on their functional group as perfluoroalkyl carboxylic acids (PFCAs) or perfluoroalkyl sulfonic acids (PFSAs) [47]. Long chain compounds are PFCAs with eight or more carbon atoms and PFSAs with six or more carbons, whereas short chain compounds are PFCAs with seven or fewer carbons and PFSAs with five or fewer carbons and ultra short chain PFAS are those with three or fewer carbons [47, 48]. Generally, an increase in the carbon chain length of PFAS compounds correlates with reduced hydrophilicity and mobility, alongside enhanced environmental persistence [49]. Therefore, PFAS with longer chains are prone to bioaccumulate, while shorter-chain PFAS tend to transfer with water and end up in plant-origin food [50]. The distinct functional groups of PFAS result in differences in mobility, sorption to solids, and potential for crop uptake, which affect their behaviour in digestate.

PFAS can enter digestate through several pathways. EPA reports that PFAS concentrations in digestate differ from those in the feedstock due to biological and chemical transformations during AD, and that some PFAS were higher in digestate than in the feedstock, potentially due to precursor breakdown [51]. This implies that PFAS fate is influenced not only by the source but also by digestion conditions and the presence of precursors, further complicating risk prediction. While long-chain PFAS are heavily monitored, the regulatory status of ultra-short-chain variants has been overlooked until now.

PFAS contamination may occur via food waste feedstocks through interactions with contact materials such as packaging, containers, and other materials that contain PFAS, or through contaminated water or soil. The application of digestate as biofertiliser can contribute to further contamination if PFAS levels in the digestate are substantial. Reported concentrations of $\sum_{38}$PFAS in soil following biosolid use ranged from 10 to 104 ng/g. In the associated crops, $\sum_{10}$PFCAs and $\sum_{6}$PFSAs were identified at concentrations up to 16 ng/g and 13 ng/g, respectively [52]. Higher concentrations up to 51.62 ng/g were reported for $\sum_{6}$PFSAs in biosolids-amended soils in another study [52]. In a more recent study, average $\sum_{79}$PFAS concentrations were higher in sewage sludge (216 ng/g) than in biosolids (152 ng/g), although one municipal wastewater biosolid reached 1310 ng/g, making biosolids the second-most-polluted source after sewage sludge [53]. An analysis of 171 contaminated sites in Michigan, US, revealed that long-chain PFAS dominate contamination in biosolids, while short- and ultra-short-chain variants account for only a minor portion of the total PFAS burden [54].

While few studies have examined PFAS in livestock compared to other species, such as marine mammals, several studies have indicated that PFAS contamination in digestate from animal manure typically occurs through the consumption of contaminated feed or water, leading to bioaccumulation in livestock. When dairy and beef cattle graze on grass or food grown on land where biosolids from sewage treatment were applied, they absorb PFAS from the contaminated matter [46]. This implies a loop in which digestate used as biofertiliser may reintroduce PFAS into

the food chain and AD processes, raising concerns about compounds with strong bioaccumulative properties, such as PFOS or PFOA. Milk and cheese samples from 2018-2020 from a dairy farm were analysed for $\sum_{16}$PFAS and found that all 22 samples contained at least one PFAS, with PFOS at the highest level of 0.881-5.68 ng/g [51]. The PFAS concentrations were determined to pose a health concern, and milk from that farm was discarded. This suggests the potential for PFAS accumulation in livestock, potentially leading to subsequent contamination of digestate produced from these sources.

Numerous methods have been employed to detect and analyse concentrations of specific PFAS in environmental and biological samples. Liquid chromatography-tandem mass spectrometry (LC-MS/MS) is the most commonly reported analytical method for PFAS detection, owing to its ability to identify and quantify a broad range of PFAS. However, the complexity of digestate poses unique challenges compared to other environmental matrices such as soil or biosolids. Digestate contains solid and liquid fractions that require different levels of processing. Additionally, the presence of organic matter and other interfering compounds may pose challenges with matrix interferences and sample preparation. Recently, a couple of emerging analytical techniques have been developed to better detect PFAS in more complex media [55]. Semi-quantitative assays, such as total oxidizable precursor (TOP) and total organic fluorine content (TOF), can analyse PFAS compounds with unknown structures [56, 57]. High-resolution mass spectrometry (HRMS), especially when coupled with liquid chromatography, is another effective method for identifying novel short-chain and ultra-short-chain PFAS in complex samples such as digestate [58].

EPA scientists have been validating analytical methods to detect PFAS in various media, including biosolids, biota, sediments, and soil. A list of the standard analytical methods developed by EPA is presented in Table 3.

Table 3: Standard Analytical Methods to measure PFAS in different media

Media	Method	Description
Aqueous and solid samples	Method 8327	Measuring $\sum_{24}$ PFAS in non-drinking water aqueous (groundwater, surface water, and wastewater) samples.
	Method 1633	Measuring $\sum_{40}$ PFAS in wastewater, surface water, groundwater, soil, biosolids, sediment, landfill leachate, and fish tissue.
Drinking Water	Method 537	Measuring $\sum_{18}$ PFAS in drinking water, including HFPO-DA (one component of the GenX processing aid technology).
	Method 533	EPA method for measuring $\sum_{25}$ PFAS in drinking water.
Source (Air) Emissions	OTM 45	Measuring $\sum_{50}$ PFAS in air emissions from stationary sources. This method focuses on semivolatile and particulate-bound PFAS.
	OTM 50	Measuring $\sum_{30}$ PFAS in air emissions from stationary sources. This method focuses on certain volatile PFAS.

As shown in Table 3, the only developed method for analysing PFAS in solid samples is EPA 1633, indicating that the investigation of PFAS in digestate remains an unexplored topic. In addition, few studies have examined how modifying this method affects performance. Sample phase influences method performance, with solid-rich matrices often requiring more pre-treatment due to the limitations in subsequent stages.

Digestate is predominantly treated as a solid, so it requires homogenisation and spiking with internal standards to account for losses during extraction. Solid-phase extraction (SPE) is used with weak anion exchange (WAX) cartridges to purify the extract, and carbon cleanup is performed using ENVI-Carb cartridges to remove remaining organic interferences. However, due to the nature of digestate, these cleanup stages may be insufficient for high organic content, potentially reducing PFAS recovery. In comparison with solid samples, aqueous samples do not require homogenisation and exhibit fewer interferences; hence, they can be directly processed through SPE and subsequent steps, further highlighting the challenges of applying the 1633 method to complex solids [59].

There are limited studies specifically examining PFAS levels in digestate; however, some studies have analysed PFAS concentrations in biosolids. Dickman and Aga developed and optimised the extraction technique of detecting PFAS in biosolid matrices, namely waste-activated sludge and lime-stabilised primary solids, using liquid chromatography tandem high-resolution mass spectrometry (LC-HRMS), offering higher resolution and broader compound detection than LC-MS/MS [60]. Although biosolid samples were analysed, the matrix complexity can be compared to that of digestate, and the analytical methods can potentially be applied to digestate. Samples were processed by solvent extraction and SPE, similar to the EPA 1633 method, but tailored for aqueous content. Instead of ENVI-Carb, the study employed graphitised carbon black, which works similarly by acting as a carbon cleanup. The study performed a target analysis using LC-HRMS of 27 known PFAS and found that the average total PFAS in waste-activated sludge was 241.4 ng/g, compared with 72.1 ng/g in lime-stabilised primary solids. Different PFAS levels reported in various studies are shown in Table 4.

Additionally, suspect screening identified several short-chain compounds, precursors, and transformation products that had not been reported previously. The findings, therefore, highlighted the presence of legacy and emerging PFAS in biosolids and demonstrated the effectiveness of a combined targeted and nontargeted approach for PFAS detection. These results provide a basis for applying PFAS detection techniques to digestate, particularly in areas where studies focused on digestate are limited.

Table 4: Comparison of reported PFAS concentrations in digestate from different feedstocks

Feedstock type	PFAS type	PFAS concentrations (ng/g)	Ref.
Food and garden organics	PFOA	0.8-1.1	[61]
	PFNA	0-0.3	
	PFDoA	0.6-0.9	
	MEFOSAA	0-1.4	
	ETFOSAA	0.5-0.7	
	8:2 FTS	0.6-0.9	
Sewage sludge	6:2 FTS	0 – 1.08	[45]
	PFHpA	0.0626 – 0.343	
	PFHxA	0 – 0.556	
	PFNA	0 – 0.0760	
	PFOA	0.361 – 0.682	
	PFDA	0 – 0.296	
	PFDoDA	0 – 0.151	
	PFBS	0 – 0.738	
	PFHxS	0.0578 – 0.104	
	PFOS	0 – 0.247	
Food waste	6:2 FTS	0.780 – 1.04	[45]
	8:2 FTS	0.441 – 1.95	
	10:2 FTS	1.69 – 3.67	
	PFHpA	0.0466 – 0.337	
	PFHxA	0.104 – 0.325	
	PFNA	0.224 – 0.798	
	PFOA	0.377 – 0.922	
	PFDA	0.647 – 2.64	
	PFUdA	0 – 1.05	
	PFDoDA	0.440 – 1.16	
	PFBS	0.0748 – 0.140	
	PFHxS	0.0929 – 0.137	
	PFOS	0 – 9.42	
	PFDS	0 – 1.07	

Analytical Methods of PFAS Detection

As with any analytical method, PFAS detection methods have limitations and challenges. SPE can only process aqueous samples, since suspended solids can clog the cartridge; hence, samples can contain a maximum of 50 mg of solids per total volume processed by SPE. The 1633 method also emphasises the importance of proper cleaning to avoid cross-contamination. Sample processing equipment, such as glassware, test tubes, blenders, etc., may contain PFAS, leading to misinterpretation of results; hence, specific cleaning solvents are provided, including methanol or methanolic ammonium hydroxide. Environmental matrices often contain traces of PFAS and their precursors, which are difficult to detect using conventional methods, primarily because standards are limited. Methods such as the total oxidisable precursor (TOP) assay and total organic fluorine (TOF) enable the identification of such precursors that cannot be detected by LC-MS/MS alone and can be used in conjunction with SPE. EPA methods can detect most PFAS by LC-MS/MS; however,

neutral and volatile PFAS are not detected by LC-MS/MS, and gas chromatography (GC) is recommended as a preferred method for their detection [55].

As summarised in Table 5, each method offers distinct advantages. Therefore, a combined approach is recommended for comprehensive PFAS characterisation in more complex matrices, such as digestate, with both solid and liquid fractions, where both legacy and emerging PFAS are likely to be present.

Table 5: Comparison of PFAS analytical methods for digestate and related matrices

Method	Detected PFAS	Strengths	Limitations	Ref.
EPA1633: SPE with LC-MS/MS	Can detect 40 types of PFAS	Well-established, standardised, validated, and can be modified to suit different types of samples and adjust to digestate.	SPE can only process aqueous samples and is prone to cross-contamination due to suspended solids. Because digestate is a complex matrix, SPE may be more easily clogged by solid particles, requiring greater cleanup.	[62]
LC-HRMS	Known and unknown PFAS through non-target analysis and suspect screening	High sensitivity and selectivity even at low concentrations	High cost, requires greater expertise, interference in samples can affect results	[60]
TOP Assay	Precursors- all oxidisable PFAS detected	Enables precursor detection that were not picked up by SPE and LC-MS/MS only. Beneficial for use with traditional techniques to detect possible precursors in digestate.	Semi-quantitative method. Only suitable for supporting other methods, such as SPE and LC-MS/MS. Only valid for oxidisable PFAS. The composition of the digestate may inhibit oxidation.	[55]
TOF analysis	All PFAS were detected by measuring fluorine content	Broad detection, high sensitivity	Matrix interferences affect results, potentially leading to inaccurate concentrations in digestate.	[55]
GC-based methods	Neutral and volatile PFAS	Useful for volatile PFAS that may be released from digestate.	Less suitable for solid and liquid matrices such as digestate	[55]

2.2.2. Microplastics

Microplastics, typically 0.1-5 mm in size, are derived from the degradation of plastic through physical, biological, and chemical processes into smaller fragments [63]. There are two categories of microplastics: primary and secondary. Primary plastics are manufactured for industrial and commercial purposes, such as electronic coatings and personal care products, including microbeads and fibres. In contrast, secondary plastics result from the fragmentation of larger plastics through mechanical abrasion, UV weathering, or microbial breakdown [64].

Early research focused on marine environments and overlooked terrestrial environments; however, increasing studies have demonstrated that terrestrial environments, particularly agricultural soils, are similarly vulnerable to microplastic contamination. Plastics, generally of petroleum origin, have a highly stable chemical structure, which makes them resistant to complete degradation and hence can persist in the environment for centuries [65]. It is estimated that up to 430,000 and 400,000 tons of microplastics are released annually onto farmland in Europe and North America, respectively, from the application of sewage sludge biosolids [63]. These figures emphasise the scale of microplastic contamination.

The shape of microplastics in the digestate is an important factor in determining their origin [66]. The presence of fibres, which typically originate from textiles and carpets, represents domestic sources; microbeads may suggest industrial origins, such as air blasting, or household origins, such as personal care and cosmetic items [67]. Regarding the frequency of microplastic shapes, recent research indicates that fibre is the dominant shape, followed by fragments and films [67].

In terms of morphology, microplastics in digestate are dominated by fibres (46.9%) and films (30.1%), with smaller contributions from granules (11.2%), flakes (10%), and spheres (1.8%). In contrast, the solid digestate shows a lower proportion of fibres (35.7%) and a complete absence of spheres, while flakes increase substantially to 20.5%, suggesting preferential retention or transformation of fragment-like particles in the solid fraction. Polymer composition also differs between phases. In digestate, PE (53.5%) and PET (47.7%) are the dominant types for fibre- and non-fibre-shaped microplastics, respectively, with notable shares of PP (25.4%) in non-fibre-shaped microplastics and PS (17.4%) and PP (16.7%) in fibre-shaped microplastics. In solid digestate, although showing a more than 10% decrease, PE remains the dominant type in fibre-shaped (41.6%), followed by PP (35.6%). In digestate, larger particles (>5 mm and 3-5 mm) constitute a substantial fraction, though mid-sized particles (1-3 mm) are also prominent. Conversely, solid digestate exhibits enrichment in smaller size classes, particularly 0.05-0.5 mm and 1-3 mm, alongside a reduced proportion of >5 mm particles [68].

These shifts in morphology and polymer composition imply selective partitioning during digestion and solid–liquid separation, likely influenced by polymer density, hydrophobicity, and particle morphology. Particle size distribution further highlights phase-dependent differences. This pattern suggests mechanical fragmentation during anaerobic digestion and/or preferential accumulation of smaller, denser particles in the solid fraction. Overall, the comparative data indicate that anaerobic treatment and subsequent solid separation modify microplastic morphology, polymer composition, and size distribution, potentially increasing the relative abundance of smaller and more fragment-

like particles in the solid digestate. Table 6 compares microplastic concentrations, sizes, and types across different feedstocks and products [65].

Table 6: Comparison of feedstock type and reported microplastic concentrations

Product	Feedstock type	Microplastic concentrations (particles/kg)	Size (mm)	Polymer type	Ref.
Compost	Municipal organic waste	2184-3416 (DW)	From 30 μm to 2 mm	-	[69]
Organic waste pulp	Organic waste	1250-1550 (WW)	>0.1	PE, bioplastic, PS	[70]
Digestate	Organic waste	167 and 22.5 (WW)	>2	PE/PP, PE, PVC, PP, PES, PS	[68]
Digestate	Household biowaste	146 (DW) 3298 (DW)	>1 >50 μm	-	[71]
Compost	Green waste	692-1814 (DW)	0.03-2	PE, PP	[69]
Manure fertiliser	Animal manure	150 (DW) 150 (DW) 144 (DW)	1.94 2.4 2.23	-	[72]
Digestate	Commercial biowaste	895 (DW)	>1	-	[73]
Digestate	Municipal Waste	75–240 (DW)	1-5	Mostly PES and PVC	[74]
Compost	Municipal Waste	39-102 (DW)	1-5	Mostly PE and PVC	[74]
Digestate	Household biowaste	70-146 (DW)	>0.5	Mostly styrene-based polymers	[74]

DW: Dry weight; WW: Wet weight; PE: polyethylene; PS: polystyrene; PP: polypropylene; PES: polyester; PVC: polyvinyl chloride

The variation in microplastics indicates that feedstock composition significantly influences microplastic concentrations, with co-digested feedstocks resulting in higher levels and thus posing greater risks. Microplastic concentrations in digestate also vary across countries, reflecting differences in waste management practices and processes [71]. In addition to food waste, plastic residues in sewage sludge and agricultural waste are also significant contributors of microplastics in digestate. Wastewater treatment plants act as a critical interception point, retaining up to 90% of influent microplastics in sewage sludge, with digestate containing microplastics 5 times higher than in raw sludge [74–76]. This suggests that the AD process may facilitate further fragmentation or release of bound particles [78]. Microplastics can also enter animal manure-derived digestate through indirect pathways, with the primary route being animal ingestion of contaminated feed, water, or bedding materials. Additionally, plastic-based materials, such as wraps and handling

materials, may introduce microplastics into the digestate obtained from AD. This is important given the diversity of feedstock types and treatment conditions used in AD [72].

The impacts of microplastics on the environment, particularly on land, are becoming increasingly evident as they disrupt soil health, harm plant and animal life, and potentially enter the food chain; however, the full extent and mechanisms remain poorly understood [63, 79, 80]. Microplastics in digestate can disperse into surrounding soil and combine with other pollutants, such as POPs and metals, potentially contributing to toxic effects in soil [81]. Sheriff et al. further highlighted that microplastics present in soil can affect the photosynthetic efficiency of crops, indicating impacts on plant health. Although digestate can potentially contain high concentrations of microplastics depending on feedstock quality, quantifying the actual impact on land contamination remains a challenge [72].

A study by Weber et al. (2025) quantified microplastics in liquid and solid digestate fertilisers, in the soil to which they were applied, and in a control soil that did not receive digestate. The digestate fertiliser was found to contain a range from 10,600-54,000 particles/kg, with a median concentration of 16,000 particles/kg. Digestate-treated soils had a median of 6,400 particles/kg (range 800-33,800), and control soil had 5,600 particles/kg when an outlier was excluded [71]. The researchers claimed that the microplastic inputs from digestate contributed only 0.9-4% of the total microplastic stock in the soil [71]. The findings from this study suggested that high background levels of microplastics can mask the impact of newly applied digestate on soils, making it a challenge to attribute the presence and accumulation of microplastics in fertilisers. Therefore, digestate may contain microplastics, but its effect may seem minor compared to background contamination, which reflects broader issues of contamination from multiple waste sources and challenges in current monitoring practices. The high background levels were attributed to years of contamination from sewage sludge, microplastic leaching, and degradation. The findings highlight that even a low level of microplastic input from digestate may remain relevant over time, particularly on land already contaminated.

Microplastics present in digestate can enter agricultural soils when applied as fertiliser, potentially leading to their accumulation in crops and, subsequently, in the food chain. This creates a pathway from digestate to soil and crops, and to livestock and humans through the ingestion of contaminated crops or animal products. Small microplastics, such as PS beads, were reported in wheat and lettuce crops, absorbed through root hairs [82]. Additionally, microplastics carry adsorbed additives such as phthalates and BPAs, which may leach into plants and pose toxicity risks [82]. Human exposure to microplastics through ingestion may pose several health risks, including chemical toxicity, inflammation, disruptions to the gut microbiome, and interference with the endocrine system [83]. However, further research is needed to better understand the health consequences of long-term exposure to microplastics, particularly through digestate-derived fertilisers.

Analytical Methods of Microplastics Detection

Because digestate is a complex matrix containing organic-rich solid-liquid fractions, detecting microplastics is more difficult than in soil or water samples, requiring greater pre-treatment to remove organic matter [84]. Identification of microplastics generally involves physical

characterisation using microscopy, followed by chemical characterisation through spectroscopy. Four preliminary steps are often required to identify microplastics based on their morphology (shape, size, colour), which include density separation, filtration, sieving, and visual sorting [85]. Standard microplastic detection methods include fluorescence microscopy, thermal/mass spectrometry, spectroscopic methods (e.g., Fourier transform infrared spectroscopy, FTIR, Raman), and visual analysis with or without light microscopy [65].

Visual techniques are not reliable for detecting microplastics, as non-plastic particles such as cellulose, keratin, paint chips, and other materials can interfere with their identification, leading to false-positive results [85]. Although larger microplastics can be easily detected visually, smaller microplastics are difficult to identify and are better detected by spectroscopy, such as FTIR and Raman. These techniques are frequently used to determine the composition of microplastics, such as PE, PP, PS, etc., using a reference spectrum library, and to identify unknown fragments in smaller microplastics [85]. Spectroscopic methods provide more information about microplastic composition and type, making them better suited for complex matrices like digestate, where interferences may reduce the effectiveness of visual techniques. These methods' strengths and limitations are compared in Table 7.

Table 7: Comparison of microplastic analytical methods for digestate [86–89]

Method/unit	Strengths	Limitations
Visual	Quick, simple, low cost	Limited as a standalone method; only preliminary with strict QA/QC. Not reliable for digestate and may cause inaccurate results
FTIR	Non-destructive, reliable, good identification of small or unknown fragments, minimal sample preparation	Because digestate is a complex matrix compared to other environmental samples, FTIR may be prone to matrix interferences.
Raman spectroscopy	Similar to FTIR, it is non-destructive, reliable, and capable of identifying small fragments.	Requires a clean surface without interference, which may limit its use for digestate with high organic matter levels
Scanning electron microscope-energy-dispersive X-ray	Simultaneously analyse morphology and elemental composition	High cost; complicated procedure; and low estimation of microplastics levels
Pyrolysis-Gas Chromatography-Mass Spectrometry	Polymers and additives detection; Does not affect by shape, size and the colour of the samples	Time-consuming and destructive; not able to detect morphological characterisation; not suitable for samples smaller than 100mm
Thermal extraction desorption-GC/MS	Adequate for identifying polymers and degradation products; less destructive than Py-GC/MS; straightforward sample preparation	Limited polymer detection range; requires complete moisture removal; high cost

Both Porterfield et al. and Yadav & Pal highlight the lack of standardised units for quantifying microplastics, which makes it difficult for regulatory bodies and researchers to compare and assess microplastic levels in samples. Three units are predominantly used for the identification and quantification of microplastics: mg/kg, particles/kg, and items/m^3, which are mass-based, count-based, and volume-based units, respectively [65]. However, there is no consistent way to convert between units without knowing the shape, size, and polymer type, thus limiting comparisons [90]. Measuring microplastics as particles/kg does not distinguish between particle sizes, potentially overlooking the ecological impacts of larger microplastics that can be ingested by larger organisms and interact with pollutants differently than smaller fragments [91, 92]. As a result, relying solely on this unit could lead to an incomplete assessment of the environmental risks posed by microplastics from digestate.

In contrast, mass-based units report the total mass of microplastics relative to the total sample mass, thereby providing greater insight into potential environmental impacts. However, like particles/kg, this unit does not account for differences in microplastic shape, which may have varying ecological effects not reflected in their mass [91, 93, 94]. Lastly, the volume-based unit is more suited to water samples than to complex matrices such as digestate. Therefore, digestate data should report both mass- and count-based units, along with microplastic size and shape, to allow better comparability between studies.

2.2.3. Heavy Metals

Heavy metals are naturally occurring elements with high atomic weights and densities relative to water, originating from both natural and human-made sources. These minerals are present throughout the Earth's crust and may be released into the environment through natural processes such as volcanic activity, weathering, and soil erosion [95]. Despite the natural presence of heavy metals in the environment, human activity has dramatically increased their presence with the rise of industrialisation, urbanisation, and agricultural applications over time. Many studies have reported that processes such as mining, metal refining, burning fossil fuels, electronic component manufacturing, agricultural fertiliser application, and treatment of municipal waste are significant sources of heavy metal accumulation that may release metals into the environment through waste streams [96, 97]. Compared with emerging contaminants such as PFAS and microplastics, heavy metals have been studied more extensively, primarily because of their widespread environmental presence from earlier industrial pollution and their well-established impacts.

Certain metals, such as copper (Cu), zinc (Zn), iron (Fe), magnesium (Mg), and manganese (Mn), are essential nutrients for biochemical and physiological functions, and inadequate concentrations of these micronutrients can result in deficiencies in plants [98]. However, in digestate, these metals are not always present at balanced levels, raising concerns about nutrient deficiency and overload depending on the amount applied to land. The difference between essentiality and toxicity lies in the concentrations at which they occur [99]. While these metals support plant growth at optimal levels, excess levels can become toxic, disrupting cellular functions. Other metals, however, including lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), serve no biological function and can be toxic even at low concentrations [100, 101].

The non-biodegradable nature of heavy metals makes them persistent in the environment, leading to bioaccumulation in soil and organisms and potentially to biomagnification through the food chain [102]. Once introduced into ecosystems, metals can persist for extended periods because they do not degrade over time like many organic pollutants. The long-term presence increases the risk of toxic exposure for terrestrial and aquatic environments and raises concerns when heavy metals are present in digestate, as it may contribute to long-term contamination of agricultural soils [102, 103].

Heavy metals may enter digestate through various sources associated with the feedstocks used in AD, including sewage sludge, animal manure, and organic waste. One of the primary routes is through sewage sludge, which often contains heavy metals from domestic wastewater, industrial effluents, and stormwater runoff. The most frequently identified metals in sewage sludge include Cu, Zn, Fe, Cr, Pb, Hg, Ni, and Cd [104]. Heavy metal concentrations in sewage sludge are rarely found to exceed regulatory limits; however, prolonged application of wastewater biosolids in agriculture may contribute to the accumulation of metals in soil. This implies that even when biosolids or digestate meet regulatory limits for heavy metals, repeated land application can lead to metal buildup in soils over time, posing environmental risks to soil health and crop growth [105]. It was found that most digestates are abundant in Zn, followed by Cu. Animal manure is also reported by literature to be another pathway for heavy metals to enter digestate, as this feedstock often contains elevated levels of Zn and Cu [106, 107]. As AD does not break down or transform heavy metals, the metals present in the original feedstocks remain in the digestate, posing potential risks when applied to land as biofertilizer.

The concentrations of heavy metals in compost, solid digestate, and liquid digestate produced from source-separated organic residues, namely Cu, Zn, Cd, Cr, Co, Ni, and Pb, have been studied in another research. Average concentrations ranged from 0.13 mg/kg for Cd to 155 mg/kg for Zn (dry weight) [108]. The researchers found that heavy metals in compost and solid digestate from kitchen and garden waste were mainly below threshold values; however, liquid digestate had significantly higher concentrations. This suggests that metal mobility and concentration are influenced not only by feedstock type but also by post-treatment separation of digestate fractions. Compost and digestate were also compared against other known sources of heavy metals, such as manure. The researchers claimed that, on a regional scale, manure contributes more to heavy metal contamination than digestate or compost. However, at the individual field scale, digestate or compost was reported to result in higher heavy metal loads than the equivalent nutrient inputs from manure [108]. The findings therefore suggest that while digestate and compost contributed only a small amount of heavy metals, repeated application in the same fields could still lead to accumulation over time, raising concerns about long-term soil health and safe use.

Elevated levels of metals in soil can inhibit microbial growth and development by damaging cells and interfering with enzymatic activity, thereby reducing microbial communities. The decreased microbial biomass, in turn, interferes with essential activities, including the breakdown of organic matter and alteration of nutrient cycling processes such as nitrification and denitrification [109, 110]. Heavy metals can also alter key soil properties, including pH, redox potential, soil aggregation, and organic matter stability, thereby affecting the soil's ability to retain nutrients. Changes in soil pH affect the mobility of metals, microbial activity, and nutrient availability, often leading to imbalances that disrupt crops [95]. Plant uptake of heavy metals can pose risks to higher trophic

levels through bioaccumulation and biomagnification. Specific crops and plants, especially vegetables, grains, and fruits, are said to contain higher levels of metals, increasing the likelihood of travelling further up the food chain [111]. The extent of metal uptake by plants, however, depends on several factors, including plant exposure to heavy metals, soil conditions, and the amount of digestate fertiliser application. Although it reported higher accumulation in edible crops, it did not mention specific metals that exhibit greater mobility in plants, which limits the ability to address food safety risks. There is, however, a specification of certain metals (e.g., Al, Cd) that lower soil pH compared to other metals (e.g., Ni, Cr) that increase soil pH [112]. Briffa et al. attributed the toxicological properties of heavy metals to their ability to form covalent bonds, enabling them to bind to organic groups and form lipophobic ions, which can generate toxic effects [102]. The mechanisms underlying heavy metal toxicity are still poorly understood, and Khalef et al. emphasised that further research is required to elucidate the mechanisms of damage [113].

While the researchers present a broad range of potential health effects, it is unclear how these effects relate to specific metal concentrations and the amount of exposure. Since heavy metals persist in the environment and the body, their presence in digestate raises concerns about long-term environmental and health management; hence, careful regulation of heavy metal concentrations in digestate is essential to ensure its use as a biofertilizer does not compromise environmental and human health.

Analytical Methods of Heavy Metal Detection

Detection of heavy metals in environmental matrices such as digestate, soil, biosolids, and compost involves multi-step procedures that typically include homogenisation, drying, digestion, and instrumental analysis. A range of standard metal-detection methods is compared, evaluated, and summarised in Table 8.

Table 8: Comparison of analytical techniques for heavy metal detection

Technique	Preparation level	Strengths	Limitations
ICP-OES	Medium	Robust, high sensitivity, simultaneous metal detection at the ng/mL level	Less sensitive than ICP-MS
ICP-MS	High	Ultra-trace detection down to parts/trillion level, ultra-sensitive detection	High equipment cost limits lab accessibility
XRF	Low	Ability to perform accurate analysis for a wide range of elements	Poor at detecting low concentrations influenced by matrix effects
AAS	Low	Cost-effective, less time-consuming, reliably analyses 62 different metals	Lacks sensitivity for certain metals

The most commonly used methods reported in the literature include inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) [114, 115]. ICP-MS is a powerful technique offering several benefits; however, it is a high-cost method that requires more sample preparation. Techniques such as X-ray fluorescence (XRF), while less sensitive than ICP methods, are advantageous for accurate quantitative analysis of a range of elements. However, XRF performance is limited in detecting low concentrations, and results may be influenced by matrix effects, which should be corrected prior to analysis [115]. Atomic absorption spectrometry (AAS) is another common technique for analysing metals in complex environmental matrices that is less time-consuming and more convenient than other methods [115]. The researchers also stated that although recent scientific advances have favoured the ICP methods, AAS remains a well-established and reliable method.

Due to the natural presence of metals in the environment, distinguishing between background levels of heavy metals and added concentrations resulting from human activity can be difficult. Khalef et al. claimed that techniques such as element speciation, profile distribution, and spatial distribution are commonly used to determine the source of toxic elements, whether they are naturally occurring (i.e., geogenic) or caused by human activity. However, it is pointed out that these methods are not reliable enough to distinguish between the sources of elements and emphasises that additional information, such as the composition of the surrounding environment, e.g. natural rocks, and known human pollution sources, e.g. industrial waste disposal and fertilisers, should be considered for a better understanding [113].

2.3. Regulations, Risks, and Knowledge Gaps

2.3.1. Current Regulatory Frameworks for Digestate Use

Regulating digestate as a biofertilizer is critical to ensuring its safe use in agriculture. These regulations vary across countries depending on environmental policies, waste classifications, and nutrient management policies. In the European Union (EU), the regulation of digestate is done through a combination of fertiliser, waste, and environmental protection policies. Under Regulation EU2019/1009, digestate is treated as a Component Material Category (CMC 5) that may be classified as either a fertiliser or waste, depending on its origin, processing, and compliance with regulatory criteria. The regulation permits digestate from source-separated inputs, such as food and garden waste, animal by-products, and crop residues, whereas higher-risk inputs, such as sewage sludge and municipal waste, are excluded. This restriction aims to reduce contamination in digestate at the source. For digestate used in organic fertilisers, the regulation establishes threshold values for heavy metals and limits visible impurities greater than 2mm, such as glass, metal, and plastics, to a maximum of 5 g/kg [116]. However, it does not currently regulate PFAS and microplastics, creating a regulatory gap given their persistence in the environment. In addition to EU regulations, national standards such as the UK's PAS110 specify digestate quality, including requirements for feedstock types, processing methods, and contaminant thresholds for potentially toxic elements, physical contaminants, and pathogens. Unlike the broader EU regulation, PAS110 focuses on digestate stability and suitability for use as biofertilizer.

In contrast to the EU's recent regulation, the US continues to rely on the EPA's 40 CFR Part 503 regulation, which covers land application of biosolids derived from municipal wastewater treatment and does not extend to digestate produced from AD systems. This EPA regulation sets traditional pollutant limits, such as those for heavy metals, that differ significantly from the EU thresholds, indicating greater tolerance for heavy metal contamination. Additionally, 40 CFR Part 503 does not impose restrictions on sewage sludge, whereas EU 2019/1009 restricts its use for digestate application. While the EPA recently released a draft risk assessment of PFOS and PFOA in biosolids, no regulatory limits currently exist, and these substances remain unmonitored under the 40 CFR Part 503. As a result, the 1993 US framework reflects traditional waste management practices that do not address newer technologies such as AD or emerging contaminants, highlighting the limitations of current regulations and the need for a more cautious regulatory approach going forward.

In Canada, digestate is regulated under the Fertilisers Act and the Fertilisers Regulations, which are enforced by the Canadian Food Inspection Agency (CFIA). Although digestate is not explicitly mentioned, it is treated as a fertiliser when it meets the regulations. Under the CFIA, digestate is classified as category A or B, depending on its feedstock quality and processing, with category A for materials that meet stricter contaminant thresholds and are suitable for unrestricted use on agricultural land, gardens, etc. In contrast, category B is for restricted use of materials with higher levels of metals, potentially reflecting feedstocks that pose a greater contamination risk [117]. Ontario Regulation 267/03, under the Nutrient Management Act, refers to digestate as the output of AD and classifies it as either an agricultural source material (ASM) or a non-agricultural source material (NASM), depending on its feedstock, which determines its land application. Digestate from feedstocks such as food waste, manure, and crop residues is classified as ASM, whereas sewage sludge or human waste falls under NASM. This is similar to the EU's 2019/1009 regulation, which also restricts the use of sewage in digestate. The Ontario regulation further specifies that digestate is considered ASM only when at least 50% of the feedstock volume originates from on-farm sources; otherwise, it is considered NASM and must meet metal concentration limits. Canada currently has no regulations that address microplastics; however, for PFAS, the CFIA's T-4-132 sets a guideline for PFOS as an indicator for PFAS contamination in commercial fertilisers (CFIA, 2025). While this is a step forward toward regulating PFAS, it applies only to biosolids and does not address digestate. Furthermore, the regulation only sets a threshold for PFOS, one of the legacies, long-chained PFAS; it does not include other common PFAS or emerging short-chain alternatives, which are unregulated in digestate.

In Australia, the Victoria EPA classifies digestate as a reportable priority waste product rather than a fertiliser, reflecting a strict policy for contamination control. However, the Victoria EPA may re-classify digestate as low risk if it meets criteria for accepted feedstocks, processing through pasteurisation, and contaminant thresholds. Similar to EU 2019/1009 and Ontario 267/03, the Victoria EPA regulation restricts sewage sludge and biosolids as feedstocks, regardless of treatment, due to the high risk of contamination. Heavy metals are regulated under this guideline for soil with limits established; however, it does not include digestate. PFAS is also regulated by the Victoria EPA, which specifies thresholds for three compounds. However, these limits apply to soil and do not mention digestate.

Additionally, the National Environmental Management Plan for PFAS (NEMP 3.0) provides further guidelines for PFAS management in organic waste, including digestate, biosolids, and food and animal waste [118]. Despite advances in regulating PFAS in digestate, the guideline does not set limits for digestate, as established for biosolids or soil by both NEMP 3.0 and the Victoria EPA, leaving a regulatory gap specific to digestate from AD. Additionally, the guidelines provided by the Victoria EPA apply only to that state and may not be consistent across all of Australia.

New Zealand currently has no specific regulations for the use of digestate on land. Instead, it relies on the Bioenergy Association's Digestate Biofertilizer Producer Accreditation Scheme (DBPAS), a voluntary scheme aligned with UK PAS110 that allows producers to demonstrate that their digestate is safe for use. Guidelines such as the DBPAS05 establish standards for digestate quality, including acceptable feedstocks and heavy metal limits (Table 9). While this guideline provides a valuable baseline for producers, its voluntary nature suggests there is no formal standard to adhere to, so producers may operate outside the scheme and remain unaccredited. Similar to the EU, digestate in New Zealand has no specific classification and may be treated as either fertiliser or waste depending on its quality, feedstock source, and accreditation by the voluntary scheme. The guideline primarily focuses on traditional contaminants, with limited information on emerging pollutants. The DBPAS11 notes the presence and potential risks of microplastics in digestate; however, as with the regulations from other countries, no thresholds are set. Similarly, there is no regulatory framework for PFAS despite their persistence and recognition as pollutants.

Table 9: Comparison of contaminant thresholds across different standards

Country/Region	Primary Policy	Heavy Metals (mg/kg)							PFAS	Microplastics	Ref.
		As	Cd	Cu	Pb	Hg	Ni	Zn			
EU	EU2019/1009	≤40	≤1.5	≤300	≤120	≤1	≤50	≤800	Restricting under REACH (2026)	<0.01% w/w	[116]
Canada	CFIA T-4-93 / T-4-132 Ontario 267/03	≤14	≤1.6	≤100	≤60	≤0.5	-	≤220	PFOS: <50 ppb	Not Reported	[119]
New Zealand	DBPAS 05	≤30	≤6.5	≤750	≤300	≤7.5	≤135	≤1250	Not Reported	Not Reported	[120]
United States	EPA 40 CFR Part 503	≤41	≤39	≤1500	≤300	≤17	≤420	≤2800	The EPA Draft Assessment (2025) suggests risk levels of 1 ppb	Not Reported	[121]
Australia	AS 4454-2012 NEMP 3.0	≤20	≤3	≤100	≤150	≤1	≤60	≤200	PFOS: <2 ppb PFOA: <1 ppb	Not Reported	[122]

2.3.2. Risk Assessment Approaches

Digestate serves as a nutrient-rich biofertiliser but may also introduce a range of persistent, potentially hazardous contaminants into agricultural land. Although the application of digestate promotes nutrient cycling, it also presents a potential pathway for pollutants to enter agricultural land and ultimately the food chain. The three primary contaminants of concern enter agricultural soil through the application of digestate. While each group of contaminants differs in their environmental behaviour, all present potential exposure pathways that may result in adverse effects in soil, the food chain, and human health. Figure 1 outlines the flow of contaminants from sources through pathways to receptors.

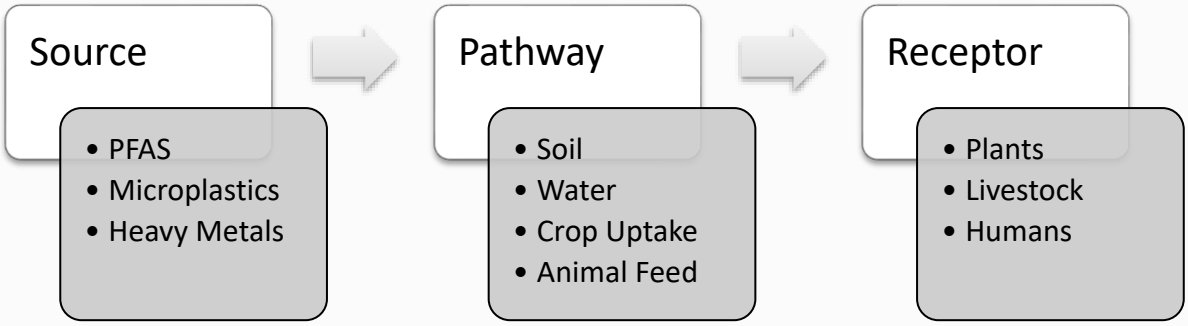


Figure 1: Contaminant sources, pathways, and receptors from digestate application

PFAS are known for their environmental persistence, resistance to degradation, and potential for bioaccumulation. Their chain length often influences the environmental risk of PFAS in digestate. Long-chain PFAS such as PFOA and PFOS have a greater affinity for organic matter and typically bind to the solid fraction of digestate [123]. Digestate applied to land, therefore, has the potential to spread PFAS into surrounding soil and around plant roots. Their physicochemical properties determine the fractionation of PFAS in soil. In soil, water-leachable PFAS are usually quite mobile and bioavailable. They might eventually change into more stable forms, like alkaline hydrolysable fractions and methanol-extractable fractions, which would lower their mobility and bioavailability [124].

Microplastics, although overlooked in regulatory frameworks, are emerging as a concern due to their increasing environmental presence. Microplastics are typically more present in the solid fraction of digestate (up to 100 times more than the liquid fraction) due to their low solubility and hydrophobic nature [125]. However, certain polymer types, namely PE and PP, can also enrich in reject water [126]. Application of digestate on land may spread microplastic contamination, as these contaminants persist in the environment and may bind to other pollutants, enhancing their mobility and bioavailability. The uptake and retention of microplastics in the roots of root vegetables, as well as their accumulation in the aerial tissues of other crops, raise significant food safety concerns. These particles can subsequently enter the diet and move through the food chain, thereby posing potential risks to human health [127]. Despite their risks, microplastics are unregulated in several countries, and no standard

quantification method or thresholds exist for monitoring concentrations in digestate, representing a significant knowledge gap.

Heavy metals are commonly present in digestate because they are found in feedstocks such as sewage sludge, industrial effluent, food waste, and manure. Digestate applied to land can spread heavy metals into surrounding soil, where their mobility, persistence, and bioavailability are influenced by soil pH, organic matter content, and crop type [128]. Since metals do not degrade, their long-term presence can lead to accumulation, even with low-level inputs, particularly when repeated digestate applications occur, with direct consequences for soil health and plant growth. High levels of heavy metals in soil can suppress enzyme activity and shift the makeup of microbial communities. Even though many studies report that metal concentrations fall below legally established safety limits, leaving the materials suitable for use, concerns remain about potential long-term accumulation, particularly when digestates are applied repeatedly [129].

Land application of digestate can introduce multiple pathways through which PFAS, microplastics, and heavy metals may enter the food chain and disrupt environmental and human health. The extent of uptake depends on the chemical properties of the contaminant, plant species, soil characteristics, and environmental conditions. For instance, mobile contaminants such as short-chain PFAS and certain metals are more readily taken up by crops, while contaminants like long-chain PFAS and most microplastics remain bound to the solid fraction of digestate, but may accumulate in soil over repeated applications. Livestock may be exposed primarily through feeding on contaminated fields, leading to human exposure through the consumption of dairy or animal products, as well as contaminated crops. Heavy metals tend to accumulate in animal tissues and disrupt cellular structures, while microplastics can damage gut integrity and disrupt metabolic processes [130]. PFAS are known to be bioaccumulative, concentrating in tissues and potentially causing adverse effects on biological systems in animals and humans [102]. While there is limited understanding of microplastic uptake in crops and their associated effects on organisms, their persistence in soil and potential to interact with other contaminants increase their exposure risks. Farm workers and residents may also face low-level but chronic exposure from regular contact with soils containing digestate biofertiliser through the consumption of locally grown produce, particularly in areas lacking regulatory guidelines or adequate monitoring; however, the effects may not be immediately apparent.

While regulatory limits for contaminants in soil, biosolids, fertilisers, and drinking water exist in many countries, there are limited guidelines specifically for digestate, which is treated as waste or fertiliser in some countries, depending on its quality and the processing of the feedstock. Furthermore, guidelines are often limited to heavy metals, while PFAS and microplastics are generally not regulated. Some countries, such as Canada and Australia, have guidelines that set PFAS thresholds; however, these are limited to only a few types of PFAS or apply only to soils.

The overall risks associated with each contaminant group from land application of digestate vary and remain uncertain due to limited data on digestate contaminant concentrations, inconsistent monitoring, and limited regulatory frameworks, especially for emerging contaminants such as PFAS and microplastics, as shown in Table 10. These knowledge gaps

make it difficult to fully characterise long-term risks given the variability in digestate composition from different feedstocks, processing conditions, and land application practices. Reported concentrations in digestate typically fall below the limits; however, repeated application of digestate may lead to gradual accumulation.

Table 10: Risk level summary of contaminants from digestate land application

Contaminant group	Risk level from digestate application	Key concerns	Knowledge gaps
PFAS	Potentially high	Persistent, bioaccumulative, linked to toxic effects. Partitioning of long- and short-chain PFAS between solid and liquid digestate may create a pathway for PFAS contamination of the surrounding land.	Despite emerging regulations, there is a lack of monitoring in digestate.
Microplastics	Uncertain	Emerging to be persistent in terrestrial environments. Digestate may spread contamination. Food waste feedstocks are of greater concern because food packaging may enter the digestive system.	No regulatory standards, no standard quantification methods, unclear pathway for uptake in crops
Heavy metals	Moderate	Risk of accumulation in soil with repeated digestate application, plant uptake and potential toxicity to organisms	Long-term accumulation effects of repeated digestate application and crop uptake

Figure 2 shows a five-step framework for determining the application of digestate on land based on examined contaminants and comparisons with thresholds, while considering exposure pathways and existing uncertainties that may influence application outcomes. This structured approach intends to support informed decisions of whether digestate can be safely applied to land, should be restricted, or avoided, depending on the extent of contamination.

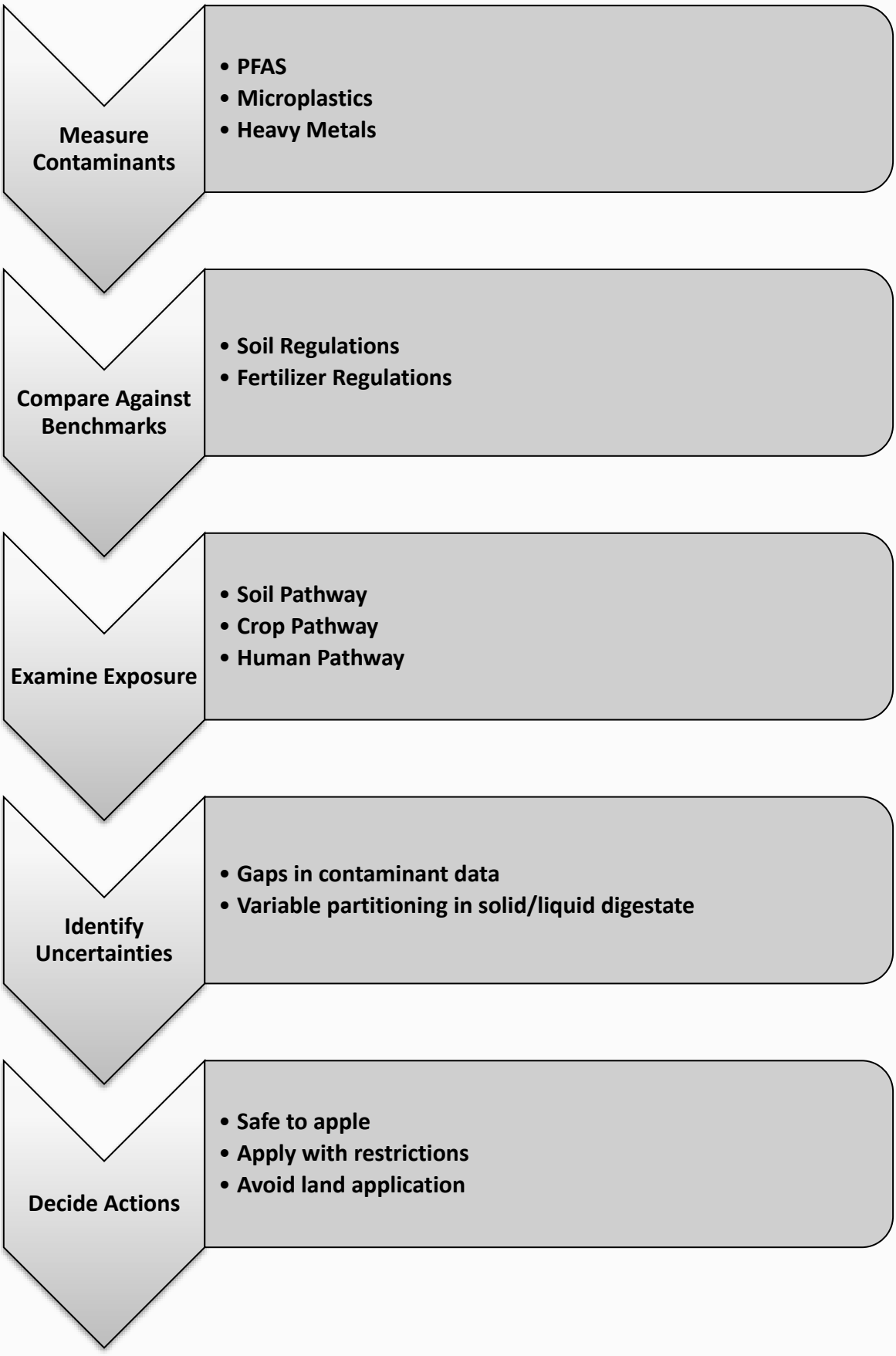


Figure 2: Five-step framework to assess land application of digestate

2.3.3. Future Directions

Despite growing research on digestate as a biofertiliser and its benefits for promoting sustainable agricultural practices, several gaps remain to ensure safe land application. While digestate provides valuable nutrients as a biofertiliser, its potential to introduce contaminants into agricultural soil and spread contamination raises environmental and health concerns. Further research is needed to understand the fate and behaviour of these contaminants in the digestate, including how they partition between the solid and liquid fractions. Thus far, most researchers have focused on tracing these pollutants in amended soil rather than in the digestate itself. Partitioning influences the mobility and persistence of these contaminants, an area that remains poorly understood. It is also important to develop standardised analytical methods for detecting these contaminants in digestate and related environmental matrices, enabling consistent monitoring and comparisons across studies to support evidence-based regulatory approaches. It can be done by modifying, combining, and developing already measured methods. Additionally, an improved understanding of exposure pathways to humans and livestock, including bioaccumulation in crops and groundwater contamination, is needed to better assess the risks associated with the land application of digestate. Addressing these concerns would require digestate-specific regulatory frameworks to incorporate monitoring protocols and apply risk assessment approaches to build confidence among farmers and the public for the safe land application of digestate.

2.4. Conclusion

The application of digestate as a biofertiliser has growing potential as a sustainable alternative to synthetic fertilisers, ultimately supporting a circular economy for the beneficial reuse of waste. However, the presence of emerging and traditional contaminants, such as PFAS, microplastics, and heavy metals, raises concerns about the safe application of digestate on agricultural land, including soil health, food safety, and human exposure. Research shows that digestate quality is influenced by various factors, including feedstock composition and AD processing, which affect contaminant concentrations and presence. While some regulatory frameworks set thresholds for traditional contaminants like heavy metals, emerging contaminants such as PFAS and microplastics are not yet fully addressed. This highlights the importance of monitoring digestate quality and assessing it to ensure the environmental benefits remain while minimising risks for both New Zealand and the global context.

3. Materials and Methods

3. MATERIALS & METHODS

3.1. Materials

This study assessed digestate quality across four feedstock types relevant to the New Zealand anaerobic digestion sector: food waste, dairy waste, manure waste, and sewage-based waste. These feedstocks were selected because they represent important organic waste streams that may be processed through anaerobic digestion and are likely to differ in both nutrient value and contaminant risk. To provide context for interpreting the digestate results, three reference materials were also analysed: soil, compost, and synthetic fertiliser.

The purpose of including these materials was to compare digestate not only as a waste-derived product, but also as a potential land-applied material. The reference samples therefore provide practical benchmarks against more familiar soil amendments and fertiliser products. The compost sample consisted of bark with added blood, bone, and gypsum, and the fertiliser sample was a granular urea-based product.

In total, seven samples were analysed:

- four digestate samples from different anaerobic digestion systems
- three reference samples: soil, compost, and fertiliser

The analytical programme was designed to assess both the potential value and the potential risk of digestate. Nutrient analysis was carried out to evaluate biofertiliser potential, while contaminant analysis covered both traditional contaminants (metals and pathogens) and emerging contaminants (PFAS and microplastics). This combined approach is important because digestate suitability for land application depends not only on nutrient content, but also on whether contaminants are present at levels that may require monitoring, management, or caution.

The digestate samples were predominantly liquid when received, while the reference samples were solid. Sample preparation therefore depended on the analytical method. For PFAS, metals, and nutrient analysis, the digestates were dried so that results could be reported on a dry-weight basis and compared more consistently across samples. For microplastics and pathogen screening, the digestates were processed in their liquid form, as this was more suitable for those methods.

The reference samples were stored at room temperature and the digestate samples were stored under refrigeration. The holding time before analysis was not recorded precisely, but was estimated to be approximately 2 to 4 weeks, as the digestate samples were received at different times and needed to be processed together for each analytical programme. This limitation should be considered when interpreting the results. In addition, images of the original samples were not recorded, which limits the visual documentation of sample condition and appearance.

Overall, the sample set was chosen to provide an initial practical comparison of digestate quality across several relevant feedstocks, while also highlighting the variability that stakeholders may need to consider when evaluating digestate for beneficial use.

3.2. PFAS Analysis

PFAS analysis was carried out using an LC-MS/MS method developed for solid environmental matrices. The samples were first homogenised and dry weight was determined. Aliquots of approximately 0.5 to 2 g were then extracted using 1% ammonia in methanol. Isotopically labelled internal standards were added before extraction for each compound analysed so that recovery and method performance could be tracked throughout the analysis. After extraction, the samples were diluted with water and analysed without a clean-up step.

PFAS were quantified by LC-MS/MS over a calibration range of 1 to 2000 ng/L. Where possible, two mass transitions were monitored for each analyte, and ion ratios were required to match the closest calibration standard within 20%. The target analyte list included compounds from the main PFAS groups examined in this study, particularly PFCAs and PFSAs, both before and after TOP assay. A quality control sample spiked at 2.5 ng/g was also used, and injection blanks were checked to confirm that the LC and MS system remained below detection limits. A 1 ng/L standard was required to be detectable.

Because digestate and sludge-type samples are complex matrices, matrix effects were an important consideration. In this method, matrix-related ion suppression or enhancement was managed mainly through the use of isotope-labelled internal standards added before extraction, together with the ability to analyse samples at higher dilution where necessary. In addition, sludge and soil samples were checked using sample spikes, and biosolid proficiency samples had previously given correct results, providing confidence that the method performed reasonably well in these matrices. However, it is important to note that uncertainty is generally higher in biosolids and similar materials because they often already contain measurable background PFAS, making method performance and detection limit assessment more difficult than in cleaner matrices.

The method validation work had shown that recoveries in biosolids were generally acceptable, although performance varied across compound groups. The carboxylic acids up to C12 and the sulfonic acids up to C8 generally showed recoveries close to 100%. The longer-chain carboxylic and sulfonic acids were more variable, typically at least 90% but sometimes as high as 140%. The neutral compounds (including MeFOSE, MeFOSA, EtFOSE, and EtFOSA) were more variable again, with internal standard recoveries typically ranging from 60% to 150%, although these compounds were generally not detected in the samples. PFDoS was analysed for, but not reported, because no suitable internal standard was available and recovery was too variable for reliable reporting.

A total oxidisable precursor (TOP) assay was also applied using a modified method based on Houtz & Sedlak (2012) [57], followed by LC-MS/MS analysis of the oxidation products. This was included because targeted PFAS analysis alone may not capture precursor compounds that can transform into terminal PFAS. The TOP assay therefore provided additional information on the likely presence of oxidisable PFAS precursors, although it should be interpreted as an indicator of precursor burden rather than a direct measurement of all precursor compounds.

The PFAS results are reported as ng/g dry weight. This is important when interpreting the data because the original digestate samples were predominantly liquid, but the analytical method

was applied using a solids-based approach. The results therefore provide a useful basis for comparing samples on a dry-weight basis, but they do not directly describe how PFAS may be distributed between the liquid and solid fractions of digestate. This should be kept in mind when using the results to inform land application decisions, future monitoring, or regulatory discussion.

A further limitation is that detection limits for biosolid-type matrices are best regarded as estimated values, because it is very difficult to obtain a truly PFAS-free sludge matrix for determining method detection limits directly. In practice, detection limits were based on soils and the weight of material used. For this reason, the PFAS results in complex digestate matrices should be interpreted as strong screening information, but with appropriate caution where background PFAS, matrix effects, and variable recoveries may influence sensitivity for some compounds.

3.3. Microplastics Analysis

Microplastics were assessed using a four-step workflow: density separation, oxidation, filtration, and particle identification by microscopy and FTIR. This approach was selected because previous studies have used H_2O_2 to digest organic matter and $ZnCl_2$ to separate lower-density particles from heavier sample material [87, 131, 132]. For digestate and similar organic-rich matrices, this type of workflow can help reduce background material before particle identification. However, the method remains sensitive to sample matrix, and this is important when interpreting the results for digestate quality assessment.

In this study, density separation was carried out before oxidation. The purpose of this step was to separate lower-density particles from the heavier matrix material first, so that less bulk material remained for the oxidation step. A $ZnCl_2$ solution was prepared at a 3:1 mass ratio with water by dissolving 6 g $ZnCl_2$ in 2 g water. The density of $ZnCl_2$ solution is typically reported to be in the range of 1.6 to 1.8 g/cm³, which has been reported as suitable for density-based separation of particles in complex samples [132]. A 1 g homogenised sample was then added to 2.5 g of the $ZnCl_2$ solution. Samples were first shaken by hand for approximately 30 seconds before subsampling, then mixed gently in the separation solution and left at room temperature for approximately 18 hours.

After density separation, the samples underwent oxidation to reduce remaining organic matter. For this step, 30% H_2O_2 was added at a 1:5 mass ratio of sample to peroxide, using 5 g H_2O_2 for 1 g of the density-separated sample solution. The bottles were sealed, placed on a Heidolph Multi Reax shaker at 700 rpm for 1 hour, and then left again at room temperature for approximately 18 hours. This step was intended to improve subsequent particle identification by reducing organic interference on the filter membranes.

The processed samples were then vacuum filtered onto alumina Anodisc membranes with a 0.2 µm pore size (Whatman®, Cytiva). Two replicate membranes were prepared for each sample to provide a basic check on analytical consistency. During filtration, 1 mL of sample solution was pipetted onto each membrane while the vacuum was running. This small filtered volume was used to avoid transferring settled residue from the bottom of the bottle onto the

membrane, which could interfere with later identification. The filtration surface was wiped with ethanol between samples to reduce cross-contamination. The membranes were then placed in a desiccator overnight to dry before analysis. This drying step should be interpreted as a method limitation, because a desiccator is not an ideal drying method for these membranes and may affect the final condition of the sample on the filter.

Particle identification was carried out using both microscopy and FTIR. Microscopy was performed using an Olympus DSX1000 digital optical microscope, with images collected at approximate scales of 50, 100, and 500 µm. FTIR analysis was performed using a PerkinElmer ATR-FTIR instrument to obtain spectra from the filtered material and compare these with known polymer spectra to assess whether microplastics may be present. Some instrument and acquisition details, including parameters such as polarisation and spectral resolution, were not available and should therefore be recognised as a limitation when interpreting the results.

Both microscopy and FTIR analysis focused mainly on the central region of the membrane, because the filtered sample was deposited primarily in that area during vacuum filtration. However, other parts of each membrane were also checked in both replicates as a basic consistency check. This is an important point for interpretation: the method provides a preliminary screening approach for possible microplastic-like particles, but it does not provide the same level of confidence as more advanced particle-specific confirmation techniques. For BANZ, industry stakeholders, and regulators, this means the results should be treated as indicative rather than definitive, and any conclusions about microplastic presence or absence should be made with caution.

Overall, the method used in this study provides a useful first step for investigating microplastics in digestate, but it also highlights the practical challenges of analysing highly organic and variable matrices. These challenges are relevant to industry and regulators because they affect how confidently microplastics can be identified, compared across studies, and eventually incorporated into future monitoring or guidance for digestate quality.

3.4. Metal Analysis

Metal analysis was undertaken to assess whether digestate from different feedstocks may contain metals at levels relevant to land application, product quality, and future monitoring needs. Metal content can influence market confidence, suitability for beneficial use, and comparison with available screening benchmarks.

The analysis used a pseudo-total microwave digestion followed by ICP-MS. The elements measured were Mg, Al, Cr, Mn, Fe, Ni, Cu, Zn, As, Cd, Hg, and Pb. These include both background/major elements and regulated trace metals that are commonly considered when assessing land-applied materials.

For each sample, approximately 100 mg dry weight was weighed into a microwave digestion vessel. The digestion reagents were 5 mL HNO_3 (69%), 1 mL HCl (37%), and 1 mL H_2O_2 (35%). Digestion was carried out using an Anton Paar Multiwave 5001 microwave digester with a

24HVT50 rotor, using a programme that ramped to 200°C over 20 minutes, held at 200°C for 20 minutes, and then auto-cooled for approximately 30 minutes.

This digestion should be interpreted as pseudo-total, not total digestion. The method did not include HF, which would be needed to fully dissolve silicate minerals and achieve true total digestion. This distinction is important when interpreting results, especially for matrices such as soil, compost, or digestate containing mineral-associated elements. The data therefore provide a strong basis for comparison between samples, but they should not be interpreted as representing complete total elemental content in all cases.

After digestion, the vessels were cooled to room temperature and diluted with 40 mL Type-1 water before analysis. Element concentrations were then measured using an Agilent 8900 ICP-QQQ-MS instrument. Calibration standards were prepared in a matrix-matched solution, and a 1 ppm certified reference material (Supelco-Multi-6-43843) was used to check calibration and recovery. A 20 ppb solution of Y and Tb was also used to monitor instrument drift and matrix effects during analysis.

The final results are reported as mg/kg on a dry-weight basis. This is important for interpretation because dry-weight reporting supports comparison between feedstocks, but it can also make concentrations appear higher than in wet samples. For industry and regulatory use, these data should therefore be viewed as a comparative dry-basis assessment of metal content across digestate and reference materials, rather than as a direct reflection of how materials would appear in their original wet form.

Overall, this method provides a practical basis for identifying which feedstocks may be associated with higher metal concentrations and which metals may require greater attention in digestate monitoring and quality assessment.

3.5. Nutrient Analysis

Nutrient analysis was carried out to assess the agronomic value of digestate and to provide a practical basis for comparing digestate with more familiar land-applied materials such as soil, compost, and fertiliser. This is important because nutrient content is one of the main factors influencing whether digestate is viewed as a useful recovered product rather than simply a waste by-product.

Total phosphorus (P) and total potassium (K) were analysed using the same digestion and ICP-MS approach described in Section 3.4, which provides a comparative measure of total elemental content on a dry-weight basis. Total nitrogen (N) was analysed separately by elemental analysis.

For nitrogen analysis, the dried samples were first ground to a fine powder using a pestle and mortar to improve sample consistency. Approximately 5 mg of each prepared sample was then weighed into tin boats and sealed to prevent sample loss during analysis. The samples were analysed using a Vario EL Cube elemental analyser (Elementar Analysensysteme, Langenselbold, Germany), with combustion and reduction temperatures set at 1150°C and 850°C, respectively. Sulphanilamide was used as the reference standard for calibration.

Nitrogen results were initially reported as dry-weight percentage and then converted to mg/kg so they could be compared directly with the phosphorus and potassium results.

Each sample was measured in duplicate for nitrogen analysis, and the duplicate results were averaged. This provides a basic check on analytical consistency for nitrogen, although it should be noted that equivalent replicate data were not available for all nutrient measurements. For stakeholders interpreting the results, the nutrient dataset therefore provides a practical comparison of total nutrient content across feedstocks, but it should not be interpreted as a direct measure of nutrient availability to plants.

Overall, this nutrient analysis was designed to identify whether digestate from different feedstocks contains nutrient levels that may support beneficial land application, while also showing how much nutrient composition can vary between digestate types.

3.6. Pathogen Analysis

Pathogen analysis was undertaken to assess whether the digestate and reference samples contained microorganisms of relevance to product hygiene and safe land application. Microbiological quality can influence treatment requirements, market confidence, and whether a product is considered suitable for beneficial use.

The microbiological work focused on:

- total culturable aerobic count
- presumptive E. coli-type colonies
- presumptive Salmonella-type colonies

The analysis used culture-based plating methods on different agars to provide an initial screening of microbial presence in the samples.

For sample preparation, 2 g of each sample was transferred into a sterile stomacher bag and mixed with 20 mL of buffered peptone water (BPW). The BPW consisted of 10 g/L peptone, 5 g/L NaCl, 3.5 g/L disodium phosphate, and 1.5 g/L monopotassium phosphate. Each sample was then homogenised in a stomacher twice for 60 seconds to disperse the material more evenly before plating.

Three plating approaches were used:

1. pour plate
2. undiluted spread plate
3. 1 in 100 dilution spread plate

Both pour and spread plate methods were included to improve the likelihood of detecting microbial growth across a range of concentrations and plating conditions.

For pour plates, aliquots of the sample-BPW mixture were combined with molten agar and poured into sterile petri dishes. This method allows growth both within and on the surface of the agar and can be useful where microbial concentrations are low or where sample distribution within the medium assists detection.

The three media used were:

- Tryptic Soy Agar (TSA) for total culturable aerobic count
- MacConkey agar (MAC) for presumptive E. coli-type / lactose-fermenting colonies
- Xylose Lysine Deoxycholate agar (XLD) for presumptive Salmonella-type colonies

Before use, the molten agars were held in a hot water bath at approximately 55°C. For each sample, three 5 mL aliquots were taken from the stomacher bag and each was mixed with 15 mL of molten MAC, XLD, and TSA, respectively, before being poured into petri dishes. The pour plates were then incubated overnight at 37°C.

For spread plates, 100 µL of the sample suspension was pipetted directly onto the surface of prepared MAC, XLD, and TSA plates and spread immediately. A 1 in 100 dilution was also prepared by mixing 10 µL of sample with 990 µL of BPW, and 100 µL of this dilution was spread onto the same three media. These spread plates were also incubated overnight at 37°C.

After incubation, the plates were examined as follows:

- TSA plates were used to estimate total culturable aerobic count
- MAC plates were examined for red colonies, which were treated as presumptive *E. coli*-type colonies
- XLD plates were examined for black colonies, which were treated as presumptive Salmonella-type colonies

Where colony growth was too dense for reliable counting, the result was recorded as TMTC (too many to count).

The results were expressed as colony-forming units per gram (CFU/g) using the plating-specific dilution factors shown in Equation 1.

$$Result\ in\ CFU/g = number\ of\ colonies \times dilution\ factor \qquad \text{(Equation 1)}$$

The dilution factors applied were:

- 2 for pour plates
- 100 for undiluted spread plates
- 10,000 for the 1 in 100 dilution spread plates

All three replicate values were retained and reported in the results section rather than reduced to a single average, so that the range and consistency of the microbiological observations could be seen directly.

This pathogen analysis should be interpreted as a screening-level culture-based assessment, rather than a full regulatory compliance test. In practical terms, the results provide useful information on whether microbial contamination may be present at levels that warrant further attention, improved treatment, or closer monitoring.

4. Results

4. RESULTS

This section presents the main findings from the digestate assessment and compares the results across the different feedstock types examined in this project. The focus is on the factors most relevant to BANZ, digestate producers, regulators, and end users: nutrient value, contaminant presence, variability between feedstocks, and how the results compare with available international benchmarks.

The results show that digestate quality is not uniform. Both nutrient content and contaminant profiles varied across the samples, which means digestate should not be treated as a single generic product for land application. Instead, its potential value and its potential risk need to be considered in relation to feedstock source, processing context, and the specific parameters being assessed.

Where suitable international limits or guidance values were available, these have been included to provide context for interpretation. These comparisons are intended as screening and decision-support references, rather than as direct statements of compliance, because many available frameworks apply to related materials such as biosolids, compost, or fertilisers rather than digestate itself.

The findings in this section should therefore be viewed as an initial evidence base for understanding digestate quality in a New Zealand context. They help identify:

- where digestate shows potential value as a nutrient-rich product
- where contaminant-related issues may require closer attention
- which feedstocks may present higher monitoring priorities
- and where current regulatory guidance remains limited, particularly for emerging contaminants

Overall, the results provide practical information to support more informed decision-making around digestate use, future monitoring, and the development of clearer guidance for the safe and beneficial land application of digestate.

4.1. PFAS

The PFAS results show a clear difference between the samples analysed before and after TOP assay. In the pre-TOP results, almost all targeted PFAS were either not detected or were below their compound-specific reporting limits. In the post-TOP results, several compounds increased, particularly short-chain PFCAs, with PFBA showing the strongest response. This pattern indicates that oxidisable PFAS precursors were likely present in several samples but were not captured by targeted analysis alone.

Table 11 shows that PFAS concentrations measured without TOP assay were generally very low across all samples, with most results reported below the relevant reporting limits (<1 or <2 ng/g depending on compound). The only clear detection in the pre-TOP results was PFOS at 4.9 ng/g in sewage digestate. Although PFOS is often reported in the literature as a common

PFAS in sludge and biosolids [134], it was not the dominant PFAS signal in this study. The strongest pattern only became clear after TOP assay, when several short-chain compounds became measurable, especially PFBA.

Following TOP assay, increases were observed across several PFAS compounds, as shown in Table 12. This is important because the TOP assay does not directly identify precursor compounds, but it does provide indirect evidence that oxidisable precursors were likely present. During the oxidation step, some precursor compounds are transformed into terminal PFAS that can then be measured by LC-MS/MS. In this study, the post-TOP results were dominated by short-chain PFCAs, particularly PFBA, which increased from below reporting limits before oxidation to concentrations greater than 300 ng/g in all digestate samples after oxidation. This indicates that targeted LC-MS/MS alone would have underestimated the broader PFAS burden in these samples.

Table 11: Concentration of PFAS compounds (ng/g dry weight) pre-TOP assay

Category	No. of C	Long/Short chain	Compound	Food digestate	Dairy digestate	Manure digestate	Sewage digestate	Soil	Compost	Fertiliser
PFCA	4	Short	PFBA	<1	<1	<1	<1	<1	<1	<1
PFCA	5	Short	PFPeA	<1	<1	<1	<1	<1	<1	<1
PFCA	6	Short	PFHxA	<1	<1	<1	<1	<1	<1	<1
PFCA	7	Short	PFHpA	<1	<1	<1	<1	<1	<1	<1
PFCA	8	Long	PFOA	<1	<1	<1	<1	<1	<1	<1
PFCA	9	Long	PFNoA	<1	<1	<1	<1	<1	<1	<1
PFCA	10	Long	PFDA	<1	<1	<1	<1	<1	<1	<1
PFCA	11	Long	PFUnDA	<1	<1	<1	<1	<1	<1	<1
PFCA	12	Long	PFDoDA	<1	<1	<1	<1	<1	<1	<1
PFCA	13	Long	PFTrDA	<2	<2	<2	<2	<2	<2	<2
PFCA	14	Long	PFTeDA	<2	<2	<2	<2	<2	<2	<2
PFSA	4	Short	PFBS	<1	<1	<1	<1	<1	<1	<1
PFSA	5	Short	PFPeS	<1	<1	<1	<1	<1	<1	<1
PFSA	6	Long	PFHxS	<1	<1	<1	<1	<1	<1	<1
PFSA	7	Long	PFHpS	<1	<1	<1	<1	<1	<1	<1
PFSA	8	Long	PFOS	<1	<1	<1	4.9	<1	<1	<1
PFSA	9	Long	PFNoS	<1	<1	<1	<1	<1	<1	<1
PFSA	10	Long	PFDS	<1	<1	<1	<1	<1	<1	<1

Table 12: Concentration of PFAS compounds (ng/g dry weight) post-TOP assay

Category	No. of C	Long/Short chain	Compound	Food digestate	Dairy digestate	Manure digestate	Sewage digestate	Soil	Compost	Fertiliser
PFCA	4	Short	PFBA	410	380	880	630	4.3	14	<1
PFCA	5	Short	PFPeA	12	3	9.6	26	3.2	<1	<1
PFCA	6	Short	PFHxA	1.3	<1	1.8	11	2.2	<1	<1
PFCA	7	Short	PFHpA	<1	<1	<1	8.3	<1	<1	<1
PFCA	8	Long	PFOA	3	3.5	13	14	1.4	1.7	<1
PFCA	9	Long	PFNoA	<1	<1	<1	5.8	<1	<1	<1
PFCA	10	Long	PFDA	<1	<1	<1	4.6	<1	<1	<1
PFCA	11	Long	PFUnDA	<1	<1	<1	3	<1	<1	<1
PFCA	12	Long	PFDoDA	<1	<1	<1	3.1	<1	<1	<1
PFCA	13	Long	PFTrDA	<2	<2	<2	<2	<2	<2	<2
PFCA	14	Long	PFTeDA	<2	<2	<2	<2	<2	<2	<2
PFSA	4	Short	PFBS	24	15	49	19	2	1.9	<1
PFSA	5	Short	PFPeS	<1	<1	<1	<1	<1	<1	<1
PFSA	6	Long	PFHxS	<1	<1	<1	<1	<1	<1	<1
PFSA	7	Long	PFHpS	<1	<1	<1	<1	<1	<1	<1
PFSA	8	Long	PFOS	<1	<1	<1	5	<1	<1	<1
PFSA	9	Long	PFNoS	<1	<1	<1	<1	<1	<1	<1
PFSA	10	Long	PFDS	<1	<1	<1	<1	<1	<1	<1

The comparison between pre-TOP and post-TOP results shows why oxidation-based screening is useful when assessing PFAS in complex materials such as digestate. Targeted LC-MS/MS only measures the compounds included in the target list, whereas TOP assay can reveal a broader precursor-related signal by converting some oxidisable precursors into measurable end products. In practical terms, this means that reliance on targeted PFAS analysis alone may lead to underestimation of PFAS-related concern in digestate, particularly where precursor compounds are present.

Among the digestate samples, sewage digestate showed the broadest post-TOP response, with increases across the greatest number of PFAS compounds. However, the number of compounds showing an increase should not be interpreted on its own as a direct measure of total precursor load. It is more useful to consider the overall change in PFAS profile after oxidation. Across all digestates, the post-TOP results were dominated by PFCAs, with PFBA showing the largest increase. Among the PFSAs, only PFBS increased consistently across most samples. This suggests that precursor compounds present in these digestates were transformed mainly into short-chain PFAS during the TOP assay, although the assay does not identify the original precursor compounds directly.

The TOP assay results should also be interpreted with caution. As highlighted by Ateia et al. (2023), failure to include ultrashort-chain PFAS such as PFPrA can lead to underestimation of precursor burden [133]. Since PFPrA was not included in this analytical suite, the precursor signal observed in this study may still underestimate the true amount of oxidisable precursor material present. In addition, TOP assay may not fully oxidise all precursor compounds [134]. For this reason, the assay should be viewed as a useful screening tool that provides additional insight into likely precursor presence, rather than a complete measure of all PFAS in digestate.

The Ontario-based study examined PFAS in digestates derived from agri-food and municipal source-separated organics [135]. Short-chain PFAS were reported more frequently than long-chain compounds, and higher PFAS concentrations were observed in whole and liquid digestates than in separated solids. Although that study did not apply TOP assay and therefore reflects PFAS in their untransformed state, it still provides useful context. In the present study, the dominance of PFBA and PFBS after TOP assay is broadly consistent with the wider literature showing that short-chain PFAS are generally more mobile and less strongly associated with solid phases than long-chain PFAS. However, the current study analysed whole samples on a dry-weight basis rather than separated liquid and solid fractions, so the results should not be interpreted as direct evidence of phase partitioning.

For BANZ, digestate producers, and regulators, one of the most important findings is that there are still limited regulatory frameworks for PFAS in digestate and related products. Existing frameworks tend to focus on a small number of PFAS, particularly PFOS, PFOA, and in some cases PFHxS. This is a significant limitation because the dominant post-TOP signal in this study came from short-chain PFAS, especially PFBA, which are not the main focus of most current thresholds. Most available PFAS criteria also apply to biosolids, not digestate. As a

result, these frameworks can only be used as screening benchmarks, not as direct compliance standards for digestate.

The Australian National Environmental Management Plan (NEMP 3.0) sets maximum allowable concentrations of PFOS + PFHxS and PFOA in biosolids for land application, with thresholds for unrestricted and restricted use [136]. All pre-TOP results in this study were below the unrestricted limits of 1.1 ng/g for PFOS + PFHxS and 3 ng/g for PFOA. In the post-TOP results, several digestate samples, particularly dairy, manure, and sewage digestate, exceeded the unrestricted-use thresholds, although they remained well below the restricted-use limits of 31 ng/g for PFOS + PFHxS and 81 ng/g for PFOA. In contrast, the soil, compost, and fertiliser reference samples remained below the unrestricted limits even after TOP assay. These comparisons are useful as a screening exercise, but they should not be treated as direct compliance assessments because the TOP assay transforms precursor compounds into measurable terminal PFAS and therefore does not reflect the original untreated sample composition.

This is particularly important because the largest post-TOP increases were associated with PFBA and PFBS, whereas the regulatory thresholds discussed above focus mainly on PFOS, PFOA, and PFHxS. This highlights a practical mismatch between current regulatory focus and the PFAS patterns revealed by precursor-sensitive testing.

Compared with the Australian NEMP 3.0, the US EPA currently addresses PFAS in biosolids through a draft risk assessment framework rather than fixed concentration limits. The draft sewage sludge risk assessment considers potential human health risks associated with PFOS and PFOA in biosolids at concentrations around 1 ppb [137]. Although it does not establish formal biosolids limits, it is relevant because it considers pathways such as crop uptake, animal uptake, soil accumulation, and drinking water contamination [137]. For stakeholders, this reinforces the point that PFAS management is not only about end-product concentrations, but also about how PFAS may move from digestate into the wider environment and food system. In Canada, the CFIA sets a maximum limit of 50 ppb for PFOS in biosolids [119]. PFOS concentrations in this study, both before and after TOP assay, remained well below that value, consistent with findings from the Ontario study [135].

Overall, the PFAS results show that digestate quality assessment based only on targeted PFAS analysis may underestimate PFAS-related concern, particularly where precursor compounds are present. The findings also show that feedstock matters, with sewage-derived digestate showing the broadest PFAS response in this study. For industry and regulators, the practical implication is that PFAS monitoring in digestate should be feedstock-aware, should recognise the value of precursor-sensitive screening methods such as TOP assay, and should interpret available biosolids-based criteria as screening references rather than direct digestate standards.

4.2. Microplastics

Microplastics were assessed in this study as a screening issue, rather than as a definitive pass/fail parameter. For BANZ, digestate producers, regulators, and end users, this is important because plastics in feedstocks can affect confidence in digestate quality, but the current evidence base and analytical methods for microplastics in digestate are still limited. The results from this study should therefore be interpreted as preliminary and mainly useful for identifying whether there is enough concern to justify stronger future monitoring and improved methods.

Microplastic screening was based on two lines of evidence:

1. FTIR spectra of material collected on the membranes, and
2. Microscopy images of particles retained after sample preparation.

Two replicate measurements were taken for each sample. As the replicate results were broadly similar, one FTIR spectrum and one microscopy image are shown for each sample.

The FTIR results did not provide strong confirmation of microplastics in most samples. As shown in Figure 3, four samples, sewage digestate, dairy digestate, compost, and soil, produced largely flat or weak spectra, with slight sloping features and no clear, well-resolved absorbance peaks.

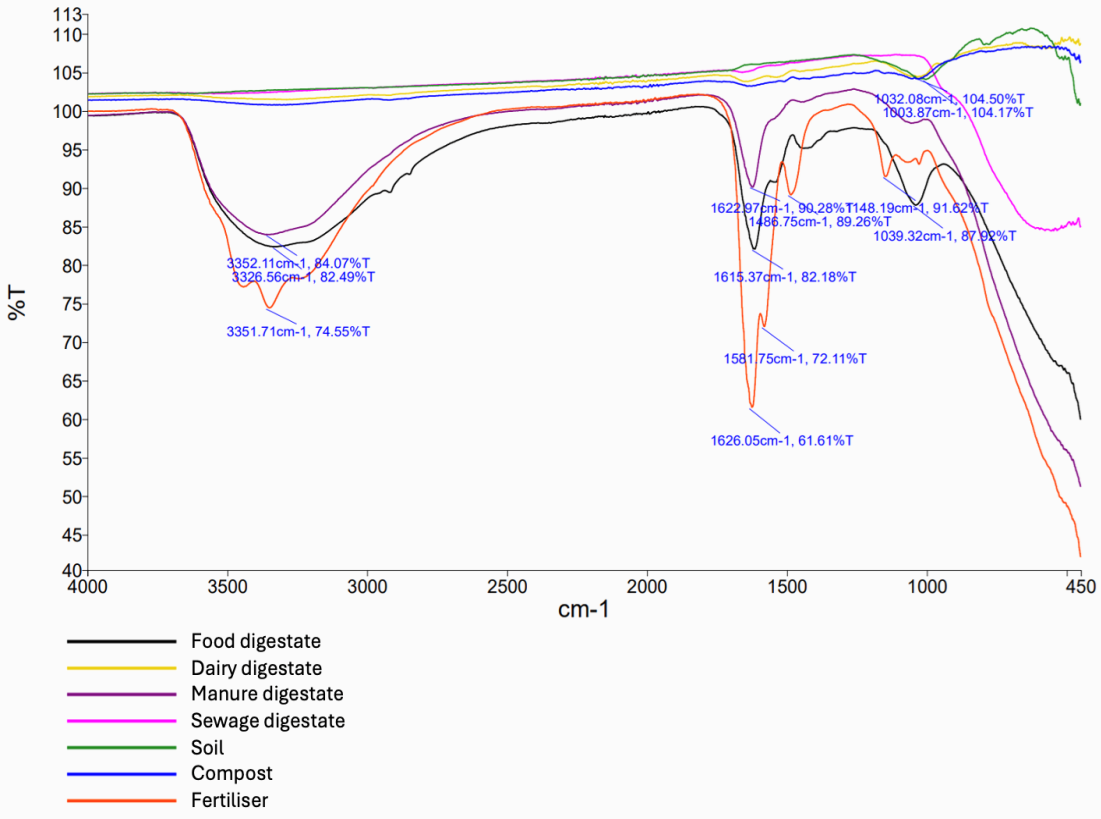


Figure 3: Overlaid FTIR spectra of the samples with labelled notable peaks

In practical terms, this means that the filtered material from these samples did not produce a strong or distinctive FTIR signal. This may reflect low detectable material on the membrane, weak absorbance from mixed residues, or interference from the sample matrix. It may also reflect the analytical difficulty of working with digestate and other heterogeneous organic-rich materials, where oxidation, filtration, sample loading, and matrix background can all affect the quality of the final spectra.

In contrast, food digestate, manure digestate, and fertiliser showed several absorbance peaks. Broad peaks at approximately 3300–3355 cm^{-1} were observed, consistent with O–H stretching, as shown in Figure 4, which presents example bond regions. These types of peaks are commonly associated with moisture and hydroxyl-containing compounds found in many organic materials [138]. Sharp peaks were also observed in the region of approximately 1600–1650 cm^{-1}, which may be related to C=O or possibly C=C bonds. However, these peaks are not specific to plastics and can occur in a wide range of non-plastic organic materials. For this reason, the FTIR results on their own do not provide sufficient evidence to confirm microplastic presence.

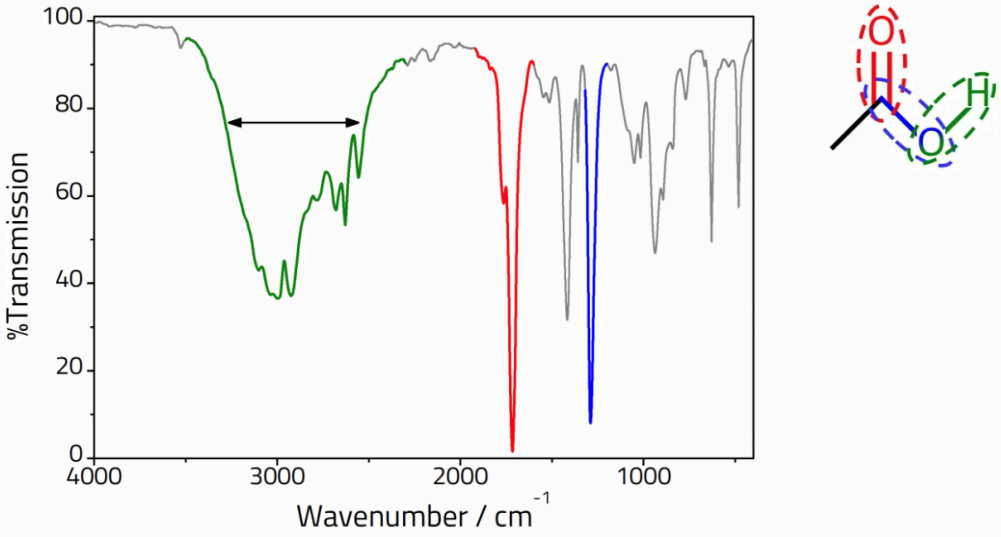


Figure 4: Example of reference spectra, indicating regions of O-H stretching, C-O, and C=O bonds (Specac Ltd, 2025)

Within the fingerprint region (500–1500 cm^{-1}), a small number of peaks were observed around 1000–1050 cm^{-1}, particularly in the fertiliser and food digestate samples, and to a lesser extent in soil and dairy digestate. These regions may correspond to C–O bonds or possibly O–H bending, as also indicated in Figure 4 [139]. Again, these features are common in many organic materials and are not, by themselves, reliable indicators of plastic polymers.

The FTIR results were therefore used only as supporting information alongside the microscopy observations.

Microscopy images were collected at different magnifications and are presented in Figure 5 using a 100 µm scale, which provided the clearest overall view of the retained particles. Suspect particles are marked in red.

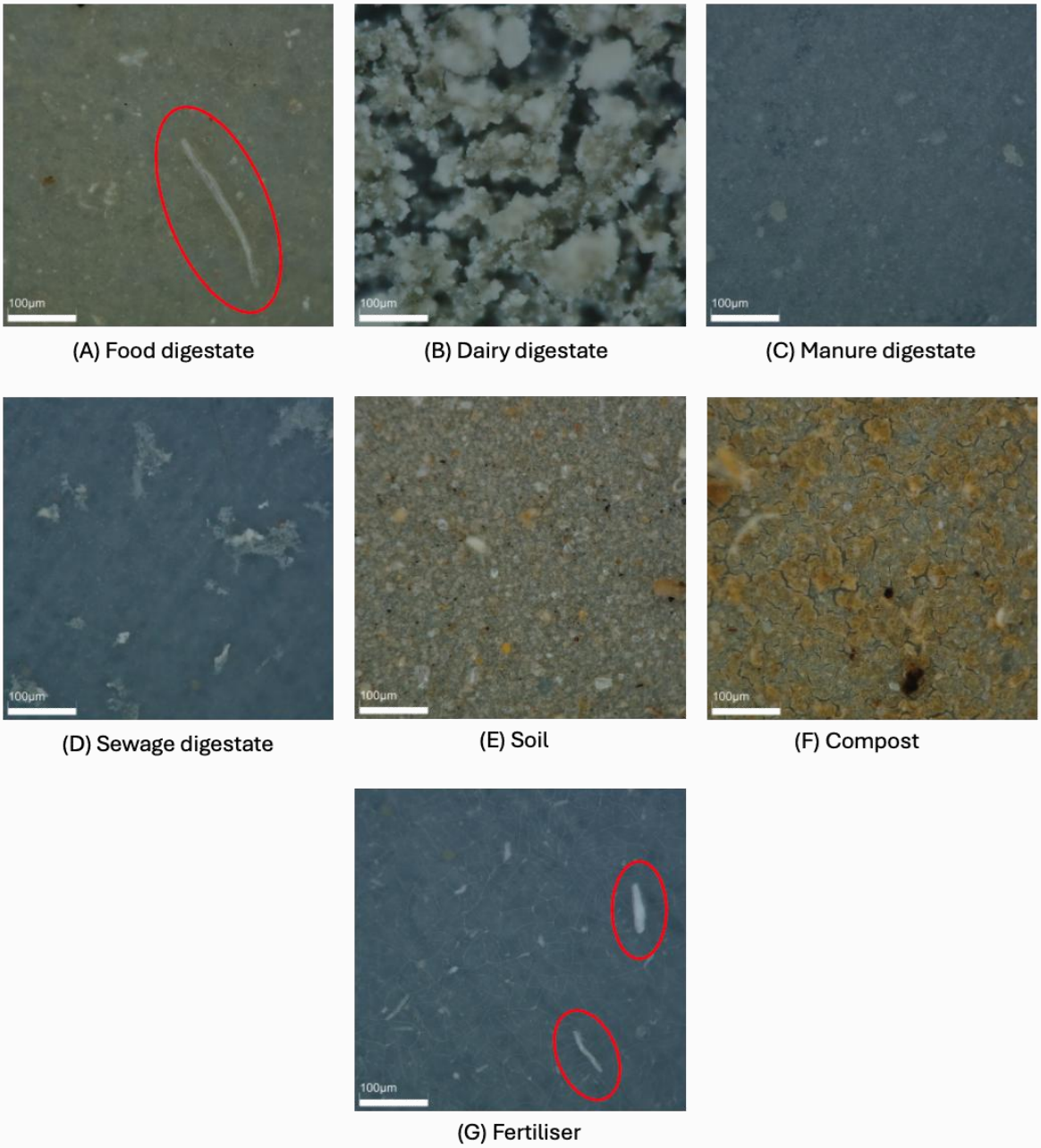


Figure 5: Examples of microscopy images of the samples at select magnifications

For most samples (B–F), the microscopy results did not show clear evidence of particles that could confidently be described as microplastics. Most observed material was irregular in shape and did not display typical features commonly associated with microplastics, such as fibres, fragments, beads, or films [72]. In dairy digestate, many irregular particles were present and may have been associated with fats or other preparation residues. Manure and sewage digestate showed very few clearly distinguishable particles, while soil and compost contained more granular particles, which are more consistent with mineral material or non-plastic sample residue than with synthetic polymers. These microscopy observations are generally consistent with the weak FTIR results obtained for the same samples. The two replicates also showed broadly similar outcomes, with only minor differences likely related to uneven sample residue on the anodisc membrane.

The main exception was the observation of some elongated, transparent particles in the food digestate and fertiliser samples. These were visually different from the irregular material seen in the other samples and had a fibre-like appearance. However, this does not provide confirmation that they were microplastics. Similar features can also arise from natural fibres, sample preparation artefacts, or contamination introduced during handling. In addition, the FTIR spectra of these samples did not show the C–H stretching region at 2800–3000 cm^{-1}, which is commonly associated with many polymer types [140]. The absence of stronger polymer-like features means these particles could not be confidently confirmed as synthetic plastics. The replicate images also showed some variability in how clearly these elongated particles could be seen, which further reduces confidence in definite identification. The most defensible conclusion is therefore that some microplastic-like particles may have been present in a small number of samples, but the current method did not provide sufficient evidence for confirmation.

Because of this uncertainty, a qualitative rather than quantitative interpretation was used. A full particle count and polymer classification were not considered reliable with the current analytical workflow. This is a useful practical point for industry and regulators: where methods are not yet sufficiently robust, the absence of clear evidence should not be interpreted as proof that microplastics are absent.

The findings from this study should also be viewed in the context of previous work. A New Zealand study examined microplastics in biowastes including biosolids, compost, and vermicompost using oxidation, density separation, and μ-FTIR for particles greater than 18 μm [141]. Microplastics were found in all samples, with the highest abundance in biosolids, and fragments were the most common particle type. The dominant polymers reported were PP and PE [141]. Similar findings were reported in an international study, which found municipal solid waste compost to contain relatively high microplastic abundance, with fragments and fibres as the dominant particle shapes and PP, PE, and PET as the main polymers [142]. Transparent microplastics were also reported to be common, with around 70% appearing transparent under light microscopy [143]. While transparent particles were observed in the food digestate and fertiliser samples in the present study, their FTIR spectra

did not confirm polymer presence, showing that transparency alone is not enough to identify microplastics.

The Ontario digestate study reported that plastics were more prevalent in digestate from municipal source-separated organics and were concentrated in the separated solids, while agri-food and liquid digestates contained no plastics [135]. This provides useful context, but the comparison should be treated with caution because the Ontario work examined separated fractions, whereas the present study analysed whole samples and did not separate liquid and solid digestate fractions. The two studies therefore do not provide directly equivalent results.

For BANZ and its stakeholders, the regulatory context is also important. Some jurisdictions have limits for plastic contamination in compost or digestate, but these mainly relate to visible or larger plastic contamination, not confirmed microplastics. In the UK, PAS100 sets a maximum limit of 0.12% m/m for plastics in compost, while PAS110 sets limits for plastics greater than 2 mm in digestate [144]. The Scottish Environment Protection Agency (SEPA) applies even stricter contamination limits, including lower limits for compost and digestate [144]. These standards are useful for controlling overall plastic contamination, but they are not directly comparable to the qualitative microplastic observations in this study.

Similarly, Renewable Energy Assurance Limited (REAL) reported that most digestate samples from green, food, and garden waste passed the relevant UK and Scottish thresholds between 2022 and 2023. This likely reflects the importance of effective feedstock pre-treatment, including the removal of larger plastic materials before anaerobic digestion. In practical terms, this is highly relevant for industry: even before microplastic-specific methods become more standardised, better control of plastic inputs at the feedstock stage is likely to be one of the most effective ways to reduce plastic contamination in digestate.

Overall, the microplastics results from this study do not provide strong evidence that microplastics were present in most samples, but they also do not demonstrate absence. Instead, the results show that microplastics assessment in digestate remains analytically challenging and that the current method should be regarded as a preliminary screening approach only. For BANZ, industry stakeholders, and regulators, the key takeaway is that current evidence and methods are not yet strong enough to support digestate-specific microplastic thresholds, and that future work should focus on better standardised methods, stronger confirmation techniques, and practical source-control measures. This is consistent with the BANZ DBPAS11 guidance, which notes that there are currently no globally agreed regulations defining acceptable levels of microplastics in digestate and no standardised methods for their analysis [145].

4.3. Metals

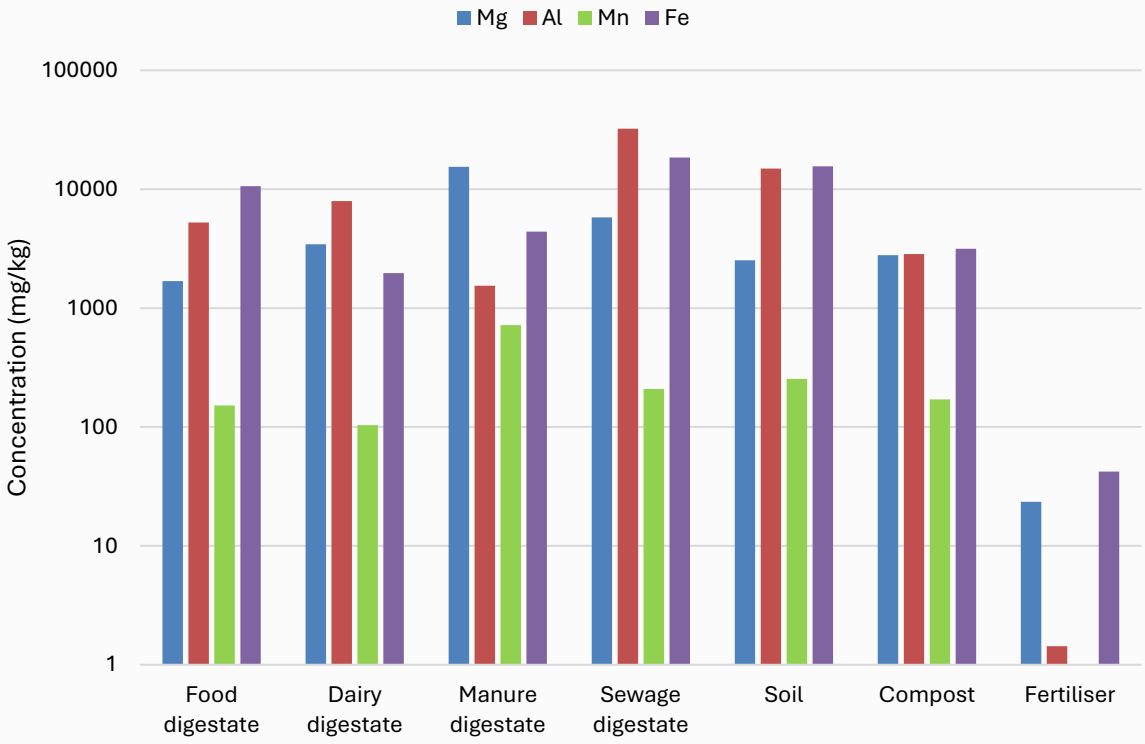
Metal concentrations were measured to help assess whether digestate from different feedstocks may be suitable for land application and where additional monitoring may be needed. For BANZ, digestate producers, regulators, and end users, this is important because metal content can affect product quality, market confidence, and how digestate compares with available screening benchmarks.

After pseudo-total microwave digestion, most sample digests were visually clear, suggesting that the digestion procedure was effective for the majority of the sample matrix. The main exception was the soil sample, which contained a small amount of residual sand- or rock-like material. This is not unexpected for soil and reflects the fact that the digestion used here was pseudo-total, not total digestion. Because HF was not used, silicate-rich mineral material would not be expected to dissolve fully. Metal concentrations measured by ICP-MS are summarised in Table 13 and shown in Figure 6, with all results reported on a dry-weight basis. Replicate analysis was not carried out for these samples, so variability between subsamples could not be quantified and the results should therefore be interpreted with appropriate caution. To improve visual comparison, Figure 6(A) and Figure 6(B) are shown on a log scale. As a result, concentrations below 1 mg/kg are not visible in the graphs, but they are included in Table 13.

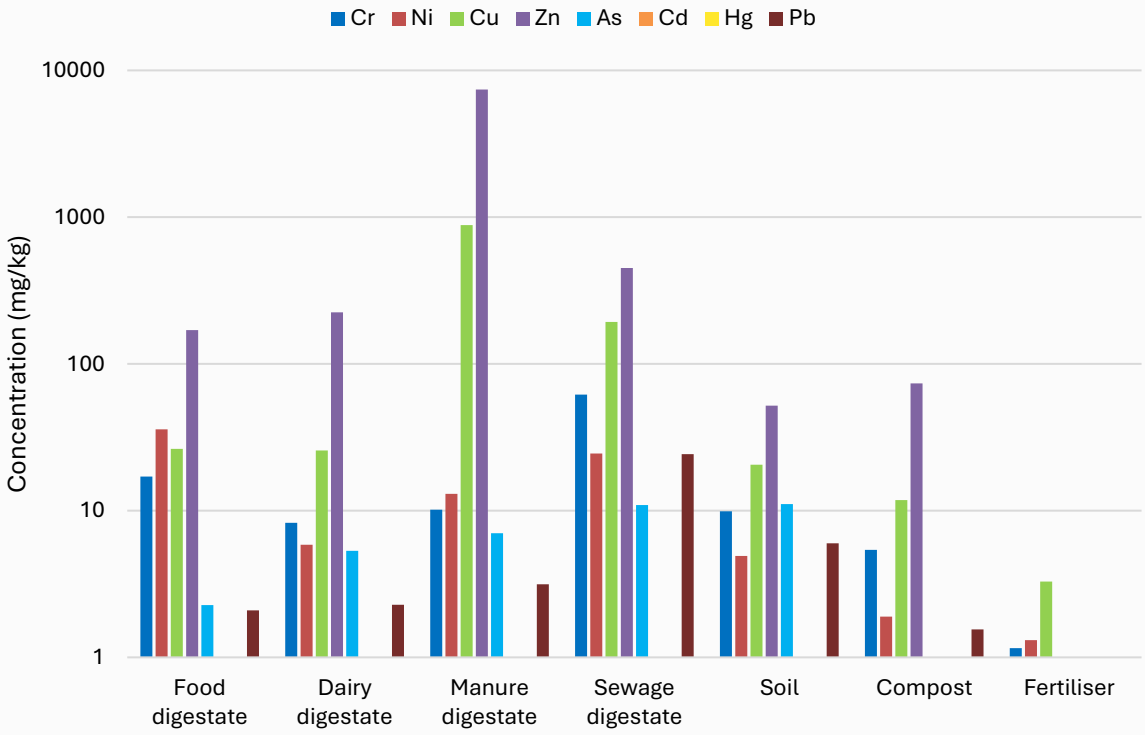
Table 13: Concentration of metals in each sample (mg/kg) dry weight basis

Metal	Food digestate	Dairy digestate	Manure digestate	Sewage digestate	Soil	Compost	Fertiliser
Mg	1687.27	3438.92	15439.50	5785.38	2525.98	2791.90	23.49
Al	5246.62	7949.00	1540.93	32248.29	14916.47	2849.50	1.43
Cr	17.07	8.26	10.15	61.72	9.90	5.40	1.15
Mn	151.71	103.57	719.02	208.46	253.89	170.68	0.34
Fe	10591.09	1969.45	4393.87	18489.42	15580.57	3152.70	42.19
Ni	35.81	5.85	12.99	24.51	4.91	1.90	1.31
Cu	26.38	25.72	882.97	193.00	20.58	11.80	3.28
Zn	169.94	224.63	7407.23	450.03	51.86	73.62	BDL*
As	2.27	5.33	7.02	10.93	11.09	0.91	0.01
Cd	0.31	0.08	0.36	0.54	0.13	0.08	0.002
Hg	0.04	0.07	0.07	0.23	0.01	BDL*	BDL*
Pb	2.09	2.28	3.15	24.23	5.99	1.55	0.13

** BDL refers to concentrations that were below the detection limit*



(A)



(B)

Figure 6: Concentration of (A) background and (B) regulated metals in the samples

At first glance, sewage digestate appears to have the highest overall metal burden, followed by soil and manure digestate. However, this overall pattern is driven mainly by the high concentrations of Al and Fe, which dominate the sewage digestate profile and are better interpreted here as background or process-related metals rather than the main regulated trace metals of concern. When the focus shifts to the metals that are more directly relevant to land-application screening, manure digestate becomes the more important sample because of its very high Zn and Cu concentrations. By contrast, the fertiliser reference sample showed very low metal concentrations overall.

Figure 6(A) shows that Al, Fe, and Mg were the dominant background metals across the sample set. Sewage digestate had the highest concentrations of Al and Fe, at 32,248 mg/kg and 18,489 mg/kg, respectively. A practical explanation for this pattern is the use of aluminium-based coagulants in wastewater treatment for removal of suspended solids and phosphorus [146]. Similarly, iron salts are commonly used in wastewater systems for sludge conditioning, odour control, and sulphide management [146,147]. These treatment-related inputs can carry through to sludge and digestate, which helps explain why sewage-derived digestate showed a different metal profile from the other feedstocks. Xu et al. (2024) also noted that such added chemicals can persist into downstream treatment processes [148]. For industry and regulators, this reinforces that sewage-derived digestate may require a different monitoring emphasis from food- or agriculturally-derived digestates.

Manure digestate showed a distinct profile. In this sample, Mg was the dominant background element, but the more important finding for screening purposes was the very high Zn concentration (7407 mg/kg) and the elevated Cu concentration (883 mg/kg), as shown in Figure 6(B). These concentrations are likely linked to the use of mineral supplements in animal feed, particularly zinc and copper, which are commonly added to support animal growth and health. These metals are not fully retained by livestock and are largely excreted in manure [149]. Because anaerobic digestion does not destroy metals, they remain in the digestate and may become concentrated on a dry-weight basis. For BANZ and digestate producers, this means manure-derived digestate may require closer attention for trace metal management than the other feedstocks examined here.

Food digestate and dairy digestate generally had lower concentrations of the regulated metals than manure and sewage digestates, although their profiles were not identical. Dairy digestate showed lower concentrations for many metals, with Al, Fe, and Mg still present at notable levels. Food digestate had relatively higher Fe and Ni than dairy digestate, but remained well below the more concerning levels seen for Zn and Cu in manure digestate. These differences likely reflect differences in feedstock composition and in the types of inputs entering each digestion system.

Among the reference materials, soil showed elevated Fe and Al, which is expected because these are common naturally occurring elements in mineral soils. Compost and fertiliser had lower overall metal concentrations, with the fertiliser sample showing very low levels that are consistent with its controlled manufactured composition. These reference materials provide

useful context for interpreting the digestate results, but they should not be treated as direct equivalents to digestate.

To help interpret the regulatory relevance of the results, Table 14 compares measured concentrations with selected international limits. Although BANZ DBPAS05 is a voluntary framework rather than a formal regulation, it still provides useful New Zealand-based screening values and is therefore included for comparison.

Table 14: Maximum heavy metal concentration limits from different country regulations

Metal	Country policy maximum limit (mg/kg) dry weight in digestate / biofertiliser / biosolids				
	NZ DBPAS05	EU 2019/1009	US EPA	Canada Ontario 267/03	
				CM1	CM2
As	30	40	41	13	170
Cd	6.5	1.5	39	3	34
Cr	1500	2*	(not reported)	210	2800
Cu	750	300	1500	100	1700
Pb	300	120	300	150	1100
Hg	7.5	1	17	0.8	11
Ni	135	50	420	62	420
Zn	1250	800	2800	500	4200

**EU limit specified for Cr(VI), not total Cr*

When compared with the values in Table 14, the measured concentrations of As, Cd, Pb, Hg, and Ni were below the cited limits across all samples. This is encouraging, but it should be interpreted as a screening comparison only, not a full compliance or risk assessment. Similar low concentrations for these metals were also reported in the Ontario digestate study [135]. It is also important to recognise that the frameworks compared here apply to different material classes and jurisdictions, and actual risk depends on factors such as application rate, receiving soil conditions, cumulative loading, and metal bioavailability. In addition, although Cr concentrations were below the limits in frameworks that consider total Cr, direct comparison with EU 2019/1009 is not appropriate because that regulation refers specifically to Cr(VI), whereas the analysis here measured total Cr by ICP-MS. Metals such as As, Cd, Cr,

Pb, and Hg can be toxic to plants and crops even at relatively low concentrations [95], so maintaining low concentrations remains important from a precautionary land-application perspective.

A more significant issue in this dataset is the concentration of Zn and Cu in manure digestate. While elements such as Zn, Mg, Cu, Fe, and Mn are essential for plant growth and physiological function [98], excessive concentrations can create concerns for land application. The Zn concentration in manure digestate (7407 mg/kg) exceeds the screening limits listed in multiple frameworks, including the DBPAS05 value of 1250 mg/kg for biofertiliser [120]. Under Ontario 267/03, non-agricultural source materials (NASM) are assessed under CM1 and CM2 categories, where exceeding CM2 means the material would not be acceptable under that criterion [150]. In this case, the Zn concentration in manure digestate exceeds both the CM1 limit of 500 mg/kg and the CM2 limit of 4200 mg/kg, meaning it would not meet the cited Ontario NASM concentration criterion. The Ontario study similarly reported elevated Zn concentrations, although those remained below CM2 [135].

The Cu concentration in manure digestate (883 mg/kg) also exceeded the screening values listed in the New Zealand, EU, and Ontario frameworks. It remained below the US EPA 40 CFR Part 503 limit for sewage biosolids (1500 mg/kg), but that value should be treated only as contextual reference because it applies to a different material class [121]. Under the Ontario framework, the manure digestate value exceeds the CM1 threshold (100 mg/kg) but remains below CM2, which means it would still fall within the Ontario upper category for NASM use [135]. Taken together, the Zn and Cu results indicate that manure-derived digestate is the main trace-metal concern in this study.

Overall, the metals data show that digestate quality differs strongly by feedstock type. For practical decision-making, the key message is that sewage-derived digestate may require closer attention for high background/process-related metals, while manure-derived digestate requires more focused attention for Zn and Cu in relation to land-application screening values. This supports a feedstock-aware monitoring approach, rather than treating all digestates as if they have the same metal risk profile.

4.4. Nutrients

Nutrient content is one of the main reasons digestate is considered for beneficial land application. For BANZ, digestate producers, end users, and regulators, the key practical question is whether digestate provides enough nutrient value to support its use as a biofertiliser or soil amendment, and how that value varies by feedstock.

The concentrations of total nitrogen (N), total phosphorus (P), and total potassium (K) are summarised in Table 15 on a dry-weight basis, reported as both mg/kg and %. The nutrient results are also shown in Figure 7, which uses a log scale so that all samples can be viewed clearly on the same graph. This was necessary because the fertiliser sample had a much higher

nitrogen concentration than the other materials, which would otherwise compress the scale for the digestate, soil, and compost results.

It is important to note that standard deviations are not shown in Table 15. Phosphorus and potassium were measured by ICP-MS as part of the metals analysis and did not include replicate analysis, which limits the strength of comparison between samples for those parameters. Nitrogen was measured in duplicate. The duplicate nitrogen results were generally consistent, except for the soil sample, where the two measurements differed by approximately 40%. This suggests possible sample heterogeneity, poor homogenisation, or analytical variation. As a result, the soil nitrogen value should be treated with more caution than the other nitrogen results.

The fertiliser sample provides a useful check on the nutrient analysis. The product label stated an NPK value of 46-0-0, and the measured values were 46.81% N, 0.02% P, and 0.002% K, as shown in Table 15. This close agreement supports the general consistency of the analytical results.

Overall, the digestate samples contained higher concentrations of most nutrients than the soil and compost reference samples, although the fertiliser sample contained by far the highest nitrogen concentration. This is consistent with the role of urea fertiliser as a concentrated and targeted nitrogen source. The digestate samples, by contrast, contained a broader nutrient profile across N, P, and K, which is relevant when considering digestate as a recovered nutrient product rather than a single-nutrient fertiliser.

Nutrient concentrations in digestate are strongly influenced by feedstock type and anaerobic digestion conditions, because digestion generally retains a large proportion of the nutrients originally present in the feedstock [151]. Literature also shows that nutrient distribution can differ between the liquid and solid fractions of digestate, with the liquid fraction typically containing lower P and higher N and K, and the solid fraction containing more P [18]. However, in the present study, the digestates were analysed as whole dried samples, not as separated liquid and solid fractions. This means the results show overall nutrient content for the sampled digestates, but do not provide direct information on nutrient partitioning between phases.

Among the digestates, total P and total K varied more strongly than total N. Dairy digestate showed the highest total P concentration at 45,834 mg/kg, while manure digestate showed the highest total K concentration at 64,076 mg/kg. These differences are likely related to feedstock composition, although the results are reported on a dry-weight basis and may also be influenced by solids content and matrix composition. In line with the literature, food digestate showed lower total P than manure digestate [41], but still contained a relatively high total K concentration (38,965 mg/kg). In contrast, dairy and sewage digestate showed lower potassium concentrations.

Table 15: Average concentration of nutrients in the samples expressed as mg/kg and percentages on a dry weight basis

	N		P		K	
Sample	mg/kg	%	mg/kg	%	mg/kg	%
Food digestate	28750	2.88	17011	1.70	38965	3.90
Dairy digestate	43650	4.37	45834	4.58	10293	1.03
Manure digestate	41400	4.14	39712	3.97	64076	6.41
Sewage digestate	43800	4.38	22806	2.28	12774	1.28
Soil	4550	0.46	1192	0.12	4435	0.44
Compost	5000	0.50	1538	0.15	1881	0.19
Fertiliser	468100	46.81	178	0.02	17	0.00

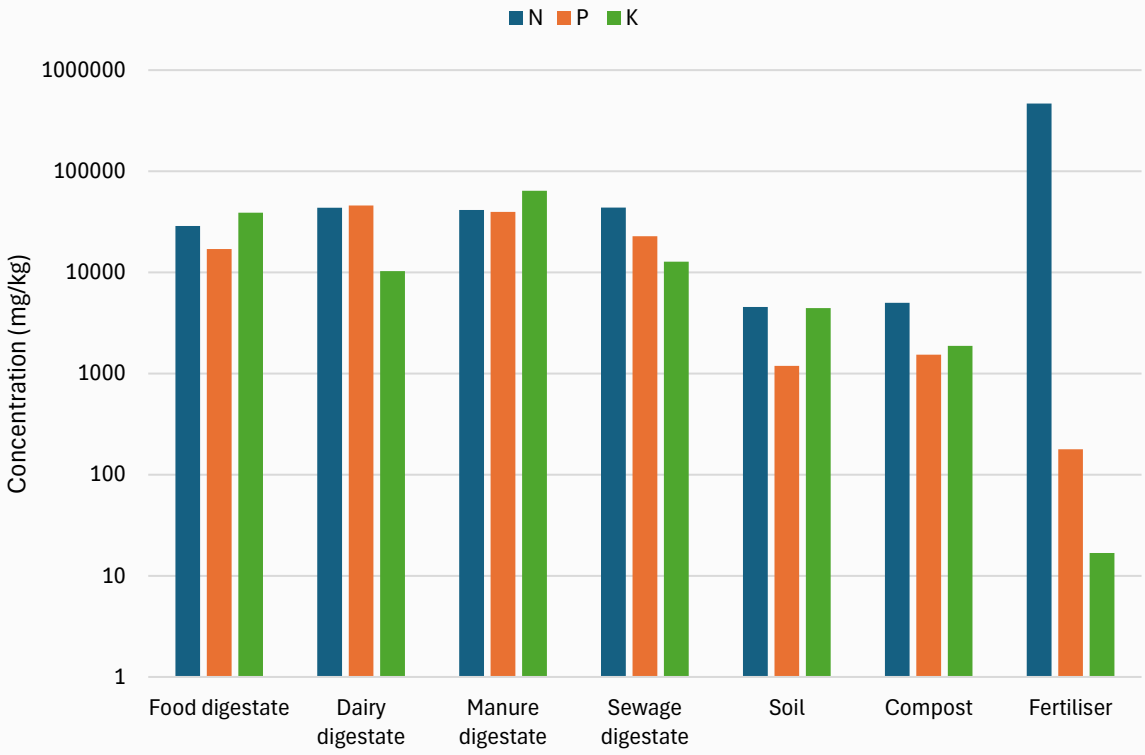


Figure 7: Concentration of nutrients (N, P, K) in the samples presented on a log scale

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Total N concentrations were comparatively similar across the digestate samples, ranging from approximately 28,000 to 44,000 mg/kg. Möller & Müller (2012) reported that total N is often broadly retained during anaerobic digestion and is related to the original feedstock nitrogen content [18]. The results here are generally consistent with that observation, although the lower total N in the food digestate compared with some published studies [5] suggests that feedstock composition, processing conditions, and nitrogen loss pathways such as ammonia volatilisation may also influence final digestate N content.

The soil and compost reference samples contained much lower nutrient concentrations overall, with total N below 5000 mg/kg and total P and total K below 2000 mg/kg. The fertiliser sample, as expected, contained very little P and K, but extremely high N. This shows that digestate differs from a conventional synthetic fertiliser: it is not a highly concentrated single-nutrient product, but it can provide a broader recovered nutrient profile.

Taken together, the results indicate that the digestates assessed in this study have biofertiliser potential [151]. The Ontario study similarly reported digestate as a useful nutrient source [135], although it found more similar nutrient profiles between agri-food and source-separated digestates than were observed here. In the present study, nutrient differences between digestates were more pronounced, particularly for K, which reinforces the point that digestate quality and value are strongly feedstock-dependent.

From a regulatory perspective, most frameworks do not set maximum limits for N, P, and K in digestate because nutrient concentrations are expected to vary depending on feedstock and processing conditions. Instead, regulation tends to focus on nutrient declaration, product classification, and appropriate use, including labelling and application practices designed to avoid excessive nutrient loading.

Under EU 2019/1009, digestate and similar products may be classified as solid or liquid organic fertilisers. For products declaring more than one nutrient, the regulation specifies minimum nutrient thresholds of 1% each for N, P_2O_5, and K_2O, with a combined nutrient total of at least 4% for solids and 3% for liquids [116]. Where only one nutrient is declared, the minimum requirement is generally higher. To allow a broad comparison with the results from this study, P_2O_5 and K_2O can be converted to elemental P and K using the relevant conversion factors [116]. On that basis, the digestates assessed here generally appear to contain nutrient concentrations consistent with nutrient-bearing products, whereas among the reference samples only the fertiliser clearly meets the nitrogen requirement as a single-nutrient product. However, this should be treated only as a general comparison, not as a statement of regulatory compliance, because the EU framework applies to specific product categories, declared nutrients, and product forms.

Overall, the nutrient data show that digestate can provide meaningful agronomic value, but that value differs between feedstocks. For industry and end users, the practical implication is that digestate should be considered as a variable nutrient product that requires feedstock-specific characterisation, rather than as a uniform substitute for synthetic fertiliser.

4.5. Pathogens

Pathogen screening was carried out to assess whether the digestate and reference samples contained microorganisms that may affect hygiene quality and the safe use of digestate on land. For BANZ, digestate producers, regulators, and end users, this is important because microbiological quality can influence treatment requirements, product acceptance, and whether additional monitoring or sanitation controls are needed before land application.

The microbiological screening used:

- TSA for total culturable aerobic count
- MAC for presumptive E. coli-type colonies
- XLD for presumptive Salmonella-type colonies

Plate counts were converted to CFU/g using the dilution factors described in Section 3.6. The results for each sample, agar, and plating method are summarised in Table 16.

The first broad observation is that microbial loads were high in most digestate samples, as well as in soil and compost. On TSA, many plates were recorded as TMTC (too many to count), showing that microbial concentrations were often too high for reliable counting at the dilution used. The only sample that showed no microbial growth on TSA was the fertiliser reference sample, which is consistent with it being a dry, granular, manufactured product that does not provide favourable conditions for microbial growth. Compost consistently showed very high total culturable aerobic counts, with all TSA plates recorded as TMTC, including the 1:100 dilution plates. This suggests that the dilution range used was still not sufficient to quantify the microbial load accurately. Food digestate also showed high counts, with values exceeding 10^6 CFU/g in the 1:100 dilution spread plates. Examples of TSA plates are shown in Figure 8.

These high total culturable aerobic counts are broadly consistent with other studies that have reported strong microbial growth in comparable organic-rich materials using general-purpose agar under similar incubation conditions. For example, Vaz-Moreira et al. (2025) reported total viable bacteria ranging from 10^4 to 10^9 CFU/g in compost samples using a general-purpose agar and incubation conditions similar to those used here [152]. The comparison should be treated as indicative only, because the sample types and analytical details are not identical, but the general pattern of high microbial activity in organic-rich matrices is consistent.

The more important practical issue for digestate quality is the presence of presumptive *E. coli*-type colonies on MAC agar. These were observed mainly in dairy digestate and sewage digestate, where growth occurred across pour plates and both undiluted and 1:100 dilution spread plates. In both of these digestates, several plates were recorded as TMTC, indicating high concentrations under the test conditions. Countable colonies were still present in the 1:100 dilution plates, which shows that these two digestates had substantially higher levels of presumptive *E. coli*-type colonies than the other digestates in this study.

Manure digestate also showed presumptive *E. coli*-type colonies, but at much lower apparent levels. Colonies were mainly observed in the pour plates and were absent from the spread plates, suggesting that any contamination present was lower than in the dairy and sewage digestates. Food digestate, soil, and fertiliser showed no presumptive *E. coli*-type colonies under the conditions used. Compost showed growth on the pour plates and undiluted spread plates, but not on the 1:100 dilution plates, indicating that presumptive *E. coli*-type colonies were present, but at lower levels than in dairy and sewage digestate.

Table 16: Colony forming units (CFU/g) for each sample for the three types of agars (TSA, MAC, XLD) and plating methods (pour plate, undiluted spread plate, 1 in 100 dilution spread plate)

Sample	Replicate	TSA (for total aerobic count)			MAC (for *E. coli*)			XLD (for *Salmonella*)		
		Pour	Spread	Spread 1:100	Pour	Spread	Spread 1:100	Pour	Spread	Spread 1:100
Food digestate	1	TMTC	TMTC	> 1,000,000	0	0	0	0	0	0
	2	TMTC	TMTC	> 1,000,000	0	0	0	0	0	0
	3	TMTC	TMTC	> 500,000	0	0	0	0	0	0
Dairy digestate	1	TMTC	TMTC	>150,000	TMTC	TMTC	100,000	0	0	0
	2	TMTC	TMTC	180,000	TMTC	TMTC	90,000	0	0	0
	3	TMTC	TMTC	> 120,000	TMTC	TMTC	230,000	0	0	0
Manure digestate	1	TMTC	>3400	230,000	4	0	0	0	0	0
	2	TMTC	>3900	>100,000	2	0	0	0	0	0
	3	TMTC	>800	TMTC	0	0	0	0	0	0
Sewage digestate	1	TMTC	TMTC	210,000	TMTC	TMTC	50,000	0	0	0
	2	TMTC	TMTC	440,000	TMTC	TMTC	70,000	0	0	0
	3	TMTC	TMTC	>140,000	TMTC	TMTC	90,000	0	0	0
Soil	1	TMTC	TMTC	120,000	0	0	0	0	0	0
	2	TMTC	TMTC	1 (clustered)	0	0	0	0	0	0
	3	TMTC	TMTC	>100,000	0	0	0	0	0	0
Compost	1	TMTC	TMTC	TMTC	TMTC	500	0	10	0	0
	2	TMTC	TMTC	TMTC	TMTC	1100	0	2	0	0
	3	TMTC	TMTC	TMTC	TMTC	1200	0	2	0	0
Fertiliser	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0

Figure 9 shows examples of MAC plates with red or dark pink colonies, which were interpreted here as presumptive E. coli-type colonies based on lactose fermentation [153]. Figure 9A shows a compost pour plate with many colonies and visible particulate matter, while Figure 9B and Figure 9C show a dairy 1:100 dilution spread plate and a manure pour plate, respectively, with fewer and more distinct colonies.

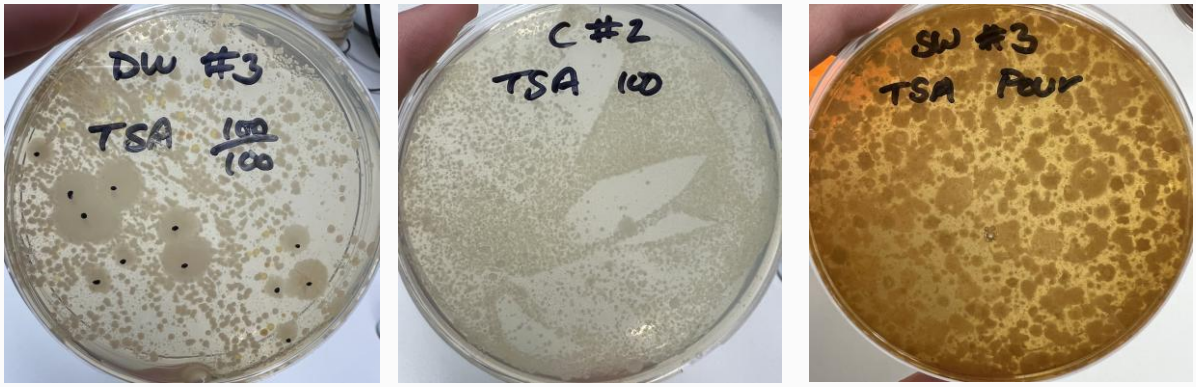

Figure 8: Examples of TSA plates showing microorganism colonies

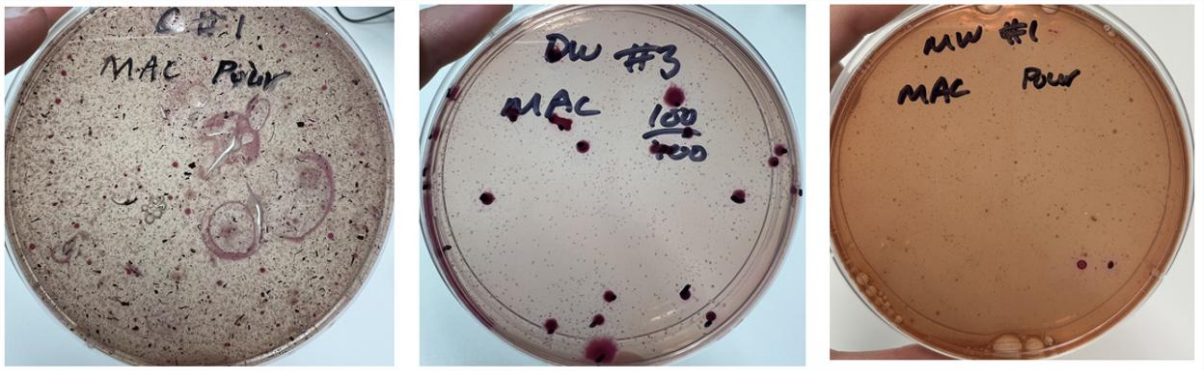

Figure 9: Examples of MAC plates with *E. coli* colonies (A) Pour plate, (B) Spread plate, (C) 1:100 dilution spread plate

The pattern observed here is broadly consistent with previous studies reporting *E. coli* in sewage-related and digestate materials. Wójcik-Fatla et al. (2024) reported average *E. coli* concentrations of 1.7×10^4 CFU/g in sewage sludge and 1.7×10^6 CFU/g in agricultural digestate [154]. Although the present study used a screening approach and several plates were TMTC, the high apparent levels seen in dairy and sewage digestates are broadly consistent with those earlier findings [154]. Vaz-Moreira et al. (2025) also detected *E. coli* in composts derived from manure and sewage sludge, with a reported value of approximately 5000 CFU/g in sewage sludge compost [152]. In the present study, compost showed lower

apparent levels than the dairy and sewage digestates, but still showed presumptive *E. coli*-type colonies on some plates.

For presumptive Salmonella-type colonies, the results were different. No colonies consistent with *Salmonella*-type growth on XLD were observed in the digestate samples, soil, or fertiliser under the conditions used. The only sample showing such colonies was compost, where black colonies were observed on the pour plates only, with counts ranging from 2 to 10 CFU/g. No such colonies were seen on the corresponding spread plates. Examples are shown in Figure 10. Figure 10A shows a compost pour plate with black colonies interpreted as presumptive *Salmonella*-type colonies, while Figure 10B shows an undiluted compost spread plate with no such colonies. Red colonies were also visible on some XLD plates, but XLD is a selective medium and black-centred colonies were used here as the screening indicator for presumptive *Salmonella*-type growth. The fact that these colonies were seen only in the pour plates suggests either a low concentration or a result that should be interpreted cautiously.

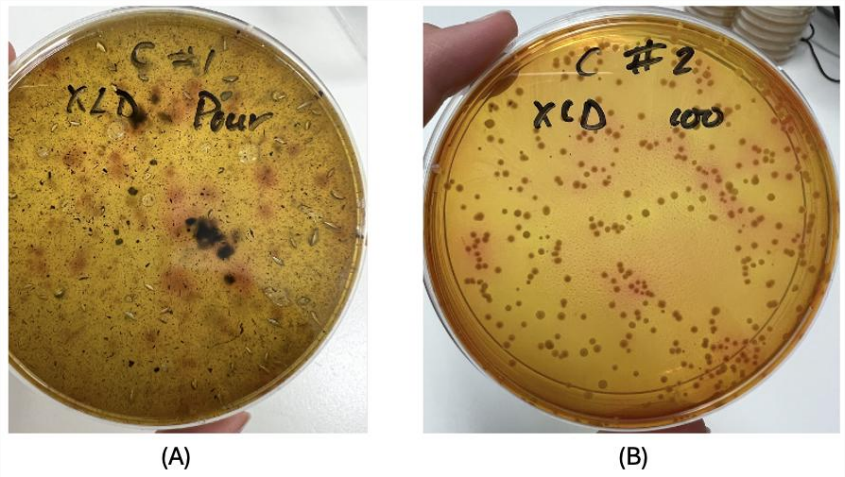

Figure 10: Examples of XLD plates with (A) and without *Salmonella* (B)

This apparent *Salmonella*-type result in compost differs from the studies by Wójcik-Fatla et al. (2024) [154] and Vaz-Moreira et al. (2025) [152], both of which did not detect *Salmonella* in the digestate or compost samples they examined. The difference may reflect sample-specific factors, processing differences, storage conditions, or differences in the analytical approach. For practical interpretation, the result should be treated as a screening-level indication rather than a definitive confirmation.

From a regulatory perspective, pathogens such as *E. coli* and *Salmonella* are among the better-established microbiological parameters for digestate, compost, and related products. The EU 2019/1009 and UK PAS110 frameworks use 1000 CFU/g as a relevant threshold for *E.*

coli in digestate-type products [116, 155], while the Australian AS4454 compost standard uses 100 CFU/g [156]. Using these values as screening references, the food digestate, manure digestate, soil, and fertiliser samples would not raise immediate concern under the conditions used here, whereas dairy digestate and sewage digestate clearly show much higher microbiological concern because presumptive *E. coli*-type colonies were still observed at high levels even after dilution. Compost also showed presumptive *E. coli*-type colonies at levels that would warrant attention, especially in relation to compost-specific screening thresholds.

For *Salmonella*, many frameworks, including EU 2019/1009, UK PAS110, and AS4454, require absence in 25 g [116, 155, 156]. The current screening method did not directly test that exact regulatory criterion, so the results here should not be interpreted as a formal compliance assessment. However, from a practical screening perspective, the absence of presumptive *Salmonella*-type colonies in the digestate samples is encouraging, whereas the presence of such colonies in the compost pour plates indicates that compost would warrant closer microbiological attention.

Overall, the pathogen results show that microbiological quality is an important issue for digestate management. The strongest concern in this dataset relates to dairy and sewage digestates, which showed high levels of presumptive *E. coli*-type colonies. For industry and regulators, the practical message is that hygienisation, treatment effectiveness, and routine microbiological monitoring remain important, particularly for higher-risk feedstocks. This is consistent with the Ontario study, which reported that *E. coli* and *Salmonella* were effectively reduced when feedstocks received full heat treatment at ≥50°C for ≥20 hours or ≥70°C for ≥1 hour [135]. These temperatures fall within mesophilic, thermophilic, or hyperthermophilic operating ranges [19] and reinforce the importance of appropriate treatment conditions where digestate is intended for land application.

5. Conclusions & Recommendations

5. CONCLUSIONS AND RECOMMENDATIONS

Key conclusions

This project provides an early New Zealand evidence base on digestate quality across selected feedstocks relevant to the anaerobic digestion sector. The results show that digestate should not be treated as a single, uniform biofertiliser product. Its value and risk profile vary with feedstock source, upstream inputs, and processing context, and these differences need to be recognised when digestate is assessed for land application or compared with external benchmarks.

Across the samples examined in this study, digestate showed clear nutrient value, supporting its potential role in nutrient recovery and beneficial reuse. However, nutrient profiles varied substantially between feedstocks, which means the agronomic value of digestate will also differ between products. In practical terms, this supports the need to view digestate as a variable product that requires feedstock-specific characterisation rather than broad assumptions about its nutrient content or suitability.

The contaminant results were also feedstock-dependent. In this dataset, manure digestate was the main trace-metal concern because of elevated zinc and copper, while dairy and sewage digestates were the main microbiological concern because of high presumptive *E. coli*-type counts under the test conditions used. Sewage digestate also showed the broadest PFAS response after TOP assay, indicating that sewage-derived feedstocks may warrant greater attention for PFAS-related screening. By contrast, the microplastics work should be interpreted much more cautiously. The method used in this study was useful as an initial screening exercise, but it did not provide strong enough evidence to confirm the presence or absence of microplastics in most samples.

A further conclusion is that regulatory coverage remains uneven. Traditional contaminants such as metals and pathogens are comparatively better addressed in international frameworks, although many of those frameworks apply to biosolids, compost, or related materials rather than digestate itself. For emerging contaminants, especially PFAS and microplastics, the available criteria and digestate-specific guidance are much more limited. For that reason, the international values used in this report should be interpreted as screening references and decision-support context, rather than as direct digestate compliance standards.

Taken together, the results suggest that digestate has genuine potential to support nutrient recovery and beneficial reuse in New Zealand, but that safe and confident land application depends on understanding the type of digestate being produced, the feedstocks entering the system, and the limits of the available data and methods. The most defensible interpretation from this study is therefore not that digestate is simply “safe” or “unsafe,” but that its suitability needs to be assessed in a feedstock-aware and evidence-based way.

Recommendations

Priority 1 – actions that can be taken now:

1. **Apply feedstock-aware monitoring rather than treating all digestates the same.** The results of this study showed clear differences between feedstocks, particularly for manure-, dairy-, and sewage-derived digestates. A practical next step for BANZ, digestate producers, and relevant regulators is therefore to adopt a more risk-based monitoring approach. Higher-risk feedstocks should receive greater attention than lower-risk streams, rather than assuming that all digestates require the same level of scrutiny. This would make monitoring more targeted, more efficient, and more consistent with the evidence generated in this project.

2. **Maintain strong routine attention to metals and hygienisation performance.** The clearest conventional contaminant issues identified in this study were elevated Zn and Cu in manure digestate and high presumptive E. coli-type counts in dairy and sewage digestates. These findings support continued routine screening of metals and microbiological quality, especially where digestate is intended for land application. For producers, this means maintaining clear quality checks around feedstock selection, treatment conditions, and product testing. For regulators and end users, it reinforces that conventional contaminants remain a key part of digestate quality assurance and should not be overlooked while attention is given to emerging contaminants.

3. **Treat PFAS as a priority screening issue for higher-risk digestates.** PFAS should be given greater attention, particularly in digestates derived from sewage-related feedstocks. In this study, targeted LC-MS/MS alone did not capture the full PFAS picture, and the TOP assay revealed a broader post-oxidation signal that would otherwise have been missed. A practical near-term approach would be to begin with targeted PFAS analysis and, where precursor burden is a concern, use a precursor-sensitive method such as TOP assay as an additional screening tool. However, TOP assay results should be interpreted carefully as screening information rather than as direct compliance values for untreated digestate.

4. **Strengthen source control for contaminants entering anaerobic digestion systems.** For both PFAS and plastic-related contamination, this study supports the view that source control is likely to be more effective than relying only on end-product testing. Producers and feedstock suppliers should therefore strengthen feedstock acceptance criteria, pre-treatment, depackaging, and upstream contamination control, particularly where packaging materials, industrial wastewater inputs, or other higher-risk contaminants may enter the system. This is a practical action that can be taken now and is likely to reduce contamination risk more effectively than relying solely on monitoring after digestion.

Priority 2 – near-term improvements:

5. **Improve microplastics methods before making threshold or absence claims.** The microplastics work in this project was useful as an initial screening exercise, but the method did not provide sufficiently strong evidence to confirm presence or absence in most samples. For that reason, the current findings should not be used to justify digestate-specific thresholds or strong statements that microplastics are absent. Future work should improve contamination control, increase replicate analysis, strengthen organic matter removal and particle recovery, and use higher-confidence confirmation methods such as μ-FTIR where available. This is important because more reliable methods are needed before industry or regulators can make confident decisions about microplastics in digestate.

6. **Improve analytical transparency and reporting quality in future studies.** This project highlighted how strongly interpretation depends on the quality of method reporting. Future digestate studies and monitoring programmes should document sample history, storage and handling, replicate strategy, uncertainty, and whether results are screening-level or more definitive. Where methods are incomplete or still developing, those limitations should be stated clearly. Better reporting will make digestate data more useful to industry, more defensible for stakeholders, and more valuable for any future regulatory or policy work.

7. **Expand PFAS method coverage in future work.** Although the PFAS results were informative, they also showed that the analytical scope could be improved. Future work should consider broader PFAS target lists, including ultrashort-chain compounds, and where appropriate examine liquid and solid digestate fractions separately. This would improve understanding of PFAS distribution and reduce the risk of underestimating precursor-related PFAS burden. For BANZ and stakeholders, this would provide a stronger basis for future decision-making and better support more informed monitoring approaches.

Priority 3 – longer-term development:

8. **Develop digestate-specific New Zealand guidance as the evidence base grows.** Current international frameworks are useful for context, but most were developed for biosolids, compost, or related materials rather than digestate itself. This limits how directly they can be applied to digestate in New Zealand. A longer-term goal should therefore be to build a stronger New Zealand evidence base across a wider range of feedstocks, process conditions, and digestate products. As that dataset grows, BANZ and its stakeholders will be in a stronger position to support digestate-specific guidance and screening values where these are justified by evidence.

9. **Support a staged approach to future regulatory development.** The results of this study do not support immediate development of firm digestate-specific thresholds for all contaminant groups, particularly for emerging contaminants such as PFAS and microplastics where the evidence base and analytical methods remain limited. A more defensible long-term approach would be staged: first improve monitoring and methods, then generate a broader New Zealand dataset, and only after that consider whether digestate-specific thresholds or guidance values are warranted. This would help ensure that any future framework is evidence-based and practical for industry use.

10. **Continue building confidence in digestate as a recovered product, not just a waste by-product.** A longer-term industry opportunity arising from this work is to strengthen how digestate is characterised and communicated to end users. The results show that digestate has real nutrient value, but also that its quality varies significantly by feedstock. Continued work on monitoring, characterisation, and clear communication of both nutrient value and contaminant risk will help support confidence in digestate as a recovered product suitable for beneficial use where appropriate. This matters for industry development, market uptake, and future policy support.

Overall conclusion

The practical conclusion of this project is that digestate has real potential to support nutrient recovery and beneficial reuse in New Zealand, but that potential depends on how digestate is produced, what feedstocks are used, and how quality is assessed and managed. Some digestates show stronger potential for beneficial land application than others. To support safe and confident use, BANZ and its stakeholders should focus on feedstock-aware monitoring, stronger source control, improved methods for emerging contaminants, and gradual development of clearer digestate-specific guidance. This report provides an initial evidence base to support that process.

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