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Quality and risk management frameworks for biosolids: An assessment of current international practice

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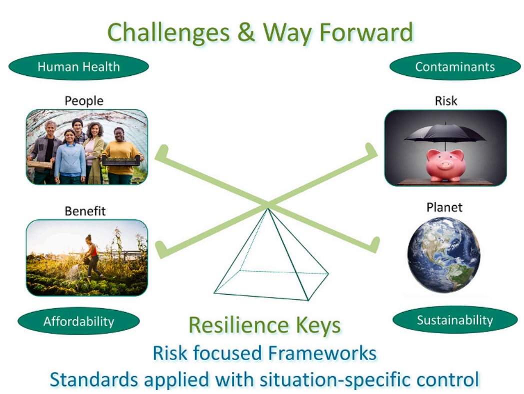
HIGHLIGHTS

- Biosolids provide an opportunity to engage and profit in the sustainability space.
- Managed risk facilitates control of emerging threats entering the terrestrial space.
- Biosolids markets are growing and would benefit from a standardized model.
- A risk management framework provides a holistic approach to biosolids management.

GRAPHICAL ABSTRACT



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ABSTRACT

Biosolids, a product of wastewater treatment, provide a valuable resource, but to optimize the use of this resource it is necessary to manage risks posed to public health and the environment. Key requirements include identifying contaminant sources and providing barriers to ensure containment and treatment while maintaining the viability and value of biosolids products. Responsibility for managing biosolids is the remit of many stakeholders but primarily it rests with private and public wastewater facilities. The global variabilities in the way biosolids resources are acknowledged, applied, and managed are substantial. For example, some countries are increasing incineration because of their ability to remove contaminants while others have experienced a proportional decrease in incineration dependent on industrial resources or regarding resource recovery costs and needs. Some jurisdictions focus on energy recovery and others on land application. A risk management framework is a tool that may provide a suitable holistic approach to biosolids management. With this focus, current instruments in practice globally to manage biosolids were assessed for the degree to which they have adopted a risk management framework. To form a basis for this assessment a set of criteria was established by concept mapping several internationally recognized standards. Guidelines for a range of developed and developing countries were then assessed against these criteria. That process enabled the identification of which current practices were holistic in terms of applying biosolids risk management principles from production to end-use.

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Through this process, risk management gaps and vulnerabilities were identified. The results reveal that the incorporation of risk standards into risk management frameworks around the world is variable for the presence of risk criteria and the scale of detail provided. Contaminant concentrations need perspective within the changing risk landscape for stakeholders and the environment while jointly the opportunities and contaminant challenges require solutions that balance risks.

1. Introduction

Outputs of conventional wastewater treatments along with effluent include the primary and secondary sludges. These sludges once extracted constitute a product commonly referred to as biosolids. Their production sits at the tail end of several processes which may include thickening, stabilisation, dewatering, and disinfection depending on the intended application (Metcalf, and Eddy, Inc. et al., 2013; US EPA, 1994). Most industrialized countries' approaches to biosolids management are broadly to encourage beneficial reuse and minimise landfills (LeBlanc et al., 2008b). Population growth and increasing urbanisation (UN, 2018) have increased sludge volumes and contaminant complexity (Li et al., 2022), creating renewed challenges for sustainable biosolids management. Wastewater and biosolids management practices are likely to be developed in response to climate, geography, financial affluence, infrastructure in place, depth of expertise engaged, political stability, and priorities. Although this is not an exhaustive list, it does display the breadth of challenges facing the world when attempting to implement priorities for biosolids management.

Countries previously worked on these issues independently with a common awareness, but the world became more connected post World War II. An example of international policies working in sympathy was demonstrated by the USA Clean Water Act which became effective in 1972 the same year as the "London Convention" formally known as the "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972" was developed. Both focus on cleaning up pollution in aquatic environments albeit with differing emphasis. Although this convention has been updated since 1972, a significant amendment for biosolids occurred in October 2022. This amendment now precludes the dumping of sewage sludge in marine environments, whereas previously this activity had been given an exception to the prohibition on dumping of waste at sea (IMO, 2022). Global collective management strategies to advise on best practices include the United Nations' sustainable development goals (SDGs), the World Health Organisation (WHO) and the Food and Agricultural Organisation (FAO). WHO and FAO have aligned their health and agricultural guidelines to the broader SGDs (United Nations, 2020; WHO, 2011, 2017, 2018a, 2018b; WHO-FAO, 2008, 2009). Management of biosolids should be made with respect to their recommendations.

At the state and national levels, the management of biosolids is frequently covered by legislation and guidelines. The primary concerns are commonly identified as the safety of the product, the location of its use and the consequences of any risk to public health (NRMMC, 2004a; NZ Ministry for the Environment, 2003; UK Govt, 2018; US EPA, 1993; WHO, 2006a, 2006b, 2015, 2017). Management of treatment grades for biosolids has primarily been achieved through stabilisation processes by reducing odour and pathogens at highly regulated wastewater treatment plants (Irwin et al., 2017) but pathogens can remain present when these controls are not adequately and consistently monitored and applied (Moya et al., 2019; Patel et al., 2020; Petrie et al., 2015). Contaminant grades use limits to monitor and control potentially toxic substance levels (Irwin et al., 2017) but these are reportedly still making it through to the biosolids products (Chu and He, 2021; Kanteraki et al., 2022). Methods of management currently employed to reduce the impacts of regulated contaminants focus on control of industrial streams (source control), post-treatment such as composting and careful control of loading rates. Not all these methods are effective for control of all types of contaminants. However, some emerging contaminants such as microplastics, synthetics, and pharmaceuticals also may not be effectively removed during the stabilisation process and are largely unregulated with a few exceptions such as triclosan and triclocarban in the EU and Polybrominated diphenyl ethers (PBDEs) in Canada (Ghirardini and Verlicchi, 2019; Gianico et al., 2021; Li et al., 2022; Taheran et al., 2017; Mohajerani and Karabatak, 2020; Okoffo et al., 2020). Noting that the threat from these emerging contaminants is more significant from domestic environments than biosolids (Clarke and Smith, 2011). However, difficult to regulate as medicines are essential for life and synthetic materials have a difficult-to-control market. Future guidelines and regulations may need to find the mechanisms and incentives to manage these contaminants as greater insight into their implications for health and the environment becomes clearer.

Production of high-quality biosolids is an important focus for all WWTPs not only for the recoverable resources' opportunity but also in support of sustainable agriculture which fosters the circular economy (Awasthi et al., 2022; Kanteraki et al., 2022; United Nations, 2022). In the EU biosolids application to land is identified as the best option in the support of the circular economy (Gianico et al., 2021). Over the last 25 years, the EU sewage sludge disposal has averaged a steady 44 % for land use, while landfill has more than halved and incineration more than doubled (Eurostat, 2023). In Australia, in 2021 73 % of biosolids were applied to land an increase from 55 % in 2010 while over the same period, stockpiles halved (Vero, 2022). The land application trend is repeated globally in addition to the focus on energy recovery (Awasthi et al., 2022; Christodoulou and Stamatelatou, 2016). The statistics reflect the critical need to preserve resources while ensuring a clean recovery process. The production of a product for reliably suitable beneficial reuse requires effective risk management.

All options for biosolids management involve risk whether it is applied to ocean disposal, land application for agriculture, emissions from incineration or through the disposal to landfill. In some jurisdictions, standards, guidelines, and regulations have been developed to support the management of these risks. Managing risk well will support the building of resilience in the system. Building resilience into a comprehensive management system needs a circular economy or sustainability principles to underpin the framework to account for both the risks and benefits (Bouziotas et al., 2023; Marchese et al., 2018). A holistic resilience approach is focused on the ability to deal with disruption with a focus on adaption while risk management anticipates and minimises known disruptions by managing hazard prevention, exposure avoidance and vulnerability protection (Mentges et al., 2023). Not accounting for the need to recover critical resources would expose sustainability goals. Assessing resilience accounts for the stressors combined with interventions provide inputs to a system that then translates into performance (Juan-García et al., 2017). Examples of the protective nature of resilience for natural resource management were demonstrated by Ayre and Nettle (2017) and Sellberg et al. (2018) which showed the benefits of adaptive, local, and collaborative planning strategies. For biosolids management resilience is primarily managed through the application of guidelines. To investigate this problem within a broad framework an analysis was conducted of current biosolids management practices operating in various parts of the world, differentiating their various strategies. Our objective was to assess the degree to which international biosolids guidance has adopted a formal risk management framework.

2. Methods

The approach to the analyses of guidelines currently in operation across a range of developed countries that have mature wastewater treatment plants operating and producing biosolids needed a common set of criteria on which to base a comparison. The guidelines and the standards used in their development are listed in Tables S7 and S8. The guidelines predominantly used the International Standards Organisation (ISO) standards. This organisation is an independent non-government, not-for-profit body and has a membership of 167 national standard bodies, including government, private and public-private entities (ISO-IEC, 2015). Using these standards provided a consistent, professionally developed and globally accepted set of management standards on which to base this investigation.

2.1. ISO standards mapped for a risk management framework

The ISO Standards relevant to biosolids management were analysed and areas of commonality were identified. The common elements were mapped to produce Tables S1 and S2 of the standards for a Quality Management system (QMS) (ISO 9001), Environmental Management System (EMS) (ISO 14001), Sludge Recovery, Recycling, Treatment and Disposal - Beneficial use of biosolids - Land application (SRRTD) (ISO 19698) and Risk (ISO 31000) (ISO, 2015a, 2015b, 2018, 2020).

2.2. Mapped standards with international best practice guides

To identify the best set of criteria for biosolids risk management the elements listed in Tables S1 and S2 were engaged. An additional dimension to these mapped elements was achieved by combining the strategies from the Plan Do Check Act (PDCA) which were based on the Shewhart cycle (Deeming, 1986) and the National Biosolids Partnership's (NBP), biosolids management program (BMP). This extended the map of criteria collated from the standards and displayed in Fig. 1 was then used with Tables S1 and S2 to identify areas of overlap or those criteria not covered by the various standards.

2.3. Guidelines and documents selected for analysis

Biosolids management guidelines from 8 countries were identified. The sources included government-released documents, national and state Environmental Protection Agencies (EPAs), industry bodies and their associated research organisations. The countries selected included the USA, Australia, New Zealand, Japan, China, Canada, the United Kingdom, and the Republic of Ireland. The guidelines identified were produced variously at national, province, prefecture, county, state, and territory levels.

The content of each guideline was examined in context with the elements identified from Tables S1 and S2. The elements in common were used to estimate a compliance factor for each heading and allowed the overall resilience to be estimated with a summary of the results tabulated in Table 3. By using the mapped standards process the objective was to apply a robust, acknowledged resilience tool to assess the guidelines. This method was similar to the method described by Champagne and Aktas (2016) known as the Leadership, in Energy and Environmental Design (LEEDS) used to assess a project's resilience and sustainability. The LEED's method currently introduces a set of 8 main categories which then assigns points through a system of checklists. The assignments are unweighted thus allowing for greater transparency (Brem et al., 2020; Rezaallah et al., 2012). A simplified version of this method was applied to the biosolids guidelines analysis, assigning dots as opposed to points to indicate the degree to which the guideline has supported the criteria identified from the mapped standards. Hence this qualitative analysis, avoided the need for a heavily quantitative one, requiring more robust data from the regulatory bodies investigated.

2.4. Identifying the gaps, resilience, and areas for improvement

Resilience was investigated respecting the existing strategies to manage biosolids. The purpose of this exercise was to highlight gaps in

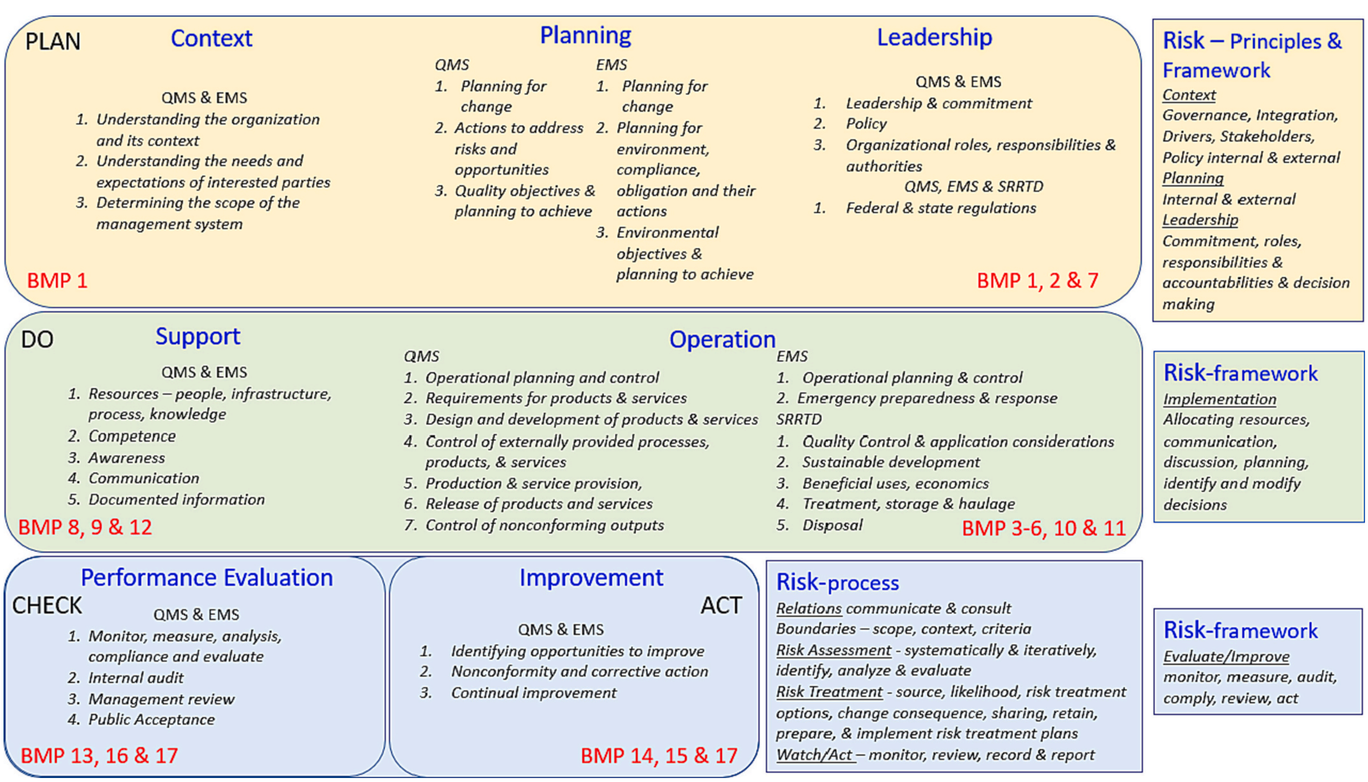

Fig. 1. International Framework Elements applied the ISO categories EMS QMS and SRRTD, how they relate to the USA NBP Good Practice and PDCA

Table 3
International framework resilience summary table.

Framework Attribute	Australia	New Zealand	USA	Canada	UK	EU - Ireland	Japan	China
Context – policy external and internal	• • •	• • •	• • •	• • •	• • •	• • •	• • •	• • •
Leadership – policy, commitment, and responsibilities	• • •	• • •	• • •	• • •	• • •	• • •	• • •	• • •
Planning - risk, compliance, environment, obligation, quality objectives, change	• • •	• • •	• • •	• • •	• • •	• •	• •	• • •
Implementation support - resources, competence, awareness, communication	• •	• •	• • •	• • •	• • •	•	• •	• •
Implementation operations - control quality, and emergency preparedness	• •	• •	• • •	• • •	• • •	• •	• •	• •
Implementation control – HACCP, source, decisions	•	• •	• • •	• •	• • •	•	•	•
Implementation of defined benefits and economics	• • •	• • •	• • •	• • •	• • •	• • •	• • •	• • •
Performance evaluation and improvement	• •	• • •	• • •	• • •	• • •	• • •	• • •	• •
Biosolids Classification Framework (BCF)	• • •	• • •	• • •	• •	•			
Treatment, Quality, Disposal	• • •	• • •	• • •	• • •	• • •	• • •	• • •	• • •
QMS EMS SRRTD Criteria	25	27	30	28	28	21	22	22
Risk design – context internal, external and values	• • •	• • •	• • •	• • •	• • •	• • •	• •	• •
Risk design – leadership, commitment, responsibilities	• • •	• • •	• • •	• • •	• • •	•		
Risk design – planning, resources	•	• •	• • •	• • •	• • •			
Risk design – implementation, decision making		•	•	• • •	• • •			
Risk evaluation and improvement		• •	• • •	• • •	• • •			
Risk relations – internal and external communication		• • •	• • •	• • •	• • •			
Risk boundaries - scope, criteria, uncertainty		• •	• •	• • •	• •	•	• •	• •
Risk assessment	• • •	• • •	• • •	• • •	• • •	• •	• •	• •
Risk treatment – options and consequence	• •	• • •	• •	• • •	• • •			
Risk watch and act – review, record, and feedback	•	• • •	• • •	• • •	• • •	•	• •	• •
Total Criteria	38	52	56	58	57	29	30	30
Resilience result	Mod	High	High	High	High	Low	Low	Low

the current strategies and identify where value can be added to the most effect. Although weighting and further analysis would have provided a more detailed view, the current method provided a means to study the targeted broader international perspective. The system used was devised by the authors and consisted of the framework attribute for which the features were identified in Fig. 1. A comparison of guidelines features reviewed with these framework attributes provided a measure of compliance see Table 3.

The first 10 framework attributes identified the response to the more traditional management systems of quality, environment, and sludge treatment. The second 10 framework attributes were based on the risk management standard. Overall, a compliance result of high, moderate, or low levels of resilience was identified for each country.

3. Results

The general trend across the guidelines viewed respecting the mapped standards shows some elements were well covered while other areas displayed less consistent coverage (see Table 3). All countries showed a strong result for context, leadership, and benefits under the quality, environmental and sludge recovery, recycling, treatment, and disposal biosolids management standards. This indicates that these results are more of a reflection of where the country is along the pathway towards a sustainable solution than a lack of drive or desire to achieve.

3.1. Mapping insights

Mapping the elements from Tables S1 and S2, the PDCA, and BMP, areas of overlap and deficits were identified. The areas in the standards that are well explored and have extensive overlap include context, planning, leadership, performance evaluation and improvement. Fig. 1 shows diagrammatically under what headings the QMS, EMS, PDCA and BMP share common elements. The attributes not covered by the traditional standards QMS, EMS and SRRTD were for risk under the implementation operation heading. Based on the standard mapping (see Fig. 1) the risk process appears to be independent of the operation tasks, but their interconnection is detailed in the ISO practical guide (ISO, 2021) which highlights the treatment of products and services with risk. This is an area of contribution that is most likely to have the largest impact at a local and regional level driven by the needs of the community, local infrastructure, financial support, and markets. This is the situation the joint research committee found when conducting their report on fertilizing products derived from biogenic wastes. The implementation of STRUBIAS pathways was likely to depend on the needs and priorities of local stakeholders (Huygens et al., 2019).

3.2. International resilience

The results are tabulated in Table 3 (see Tables S1 and S2 for more detail) with comments on the reasoning applied in the analysis located in Section 3.3. The standards criteria for the two Tables, S1 addresses quality, environmental and biosolids management while S2 addresses the management of risk. These tables at the heading level sound similar but the incorporation of the features, strategies and objectives have very different perspectives. An example of this difference is highlighted under evaluation where the QMS, EMS and SRRDT standards priorities are to measure, monitor, record, and report features. These standards primarily focus on product compliance and improvement with the purpose of quality control, safety of the product, and its application. Whereas the risk standard evaluation and improvement measure the effectiveness of the risk framework, internally and externally against KPIs, audits, and stakeholder needs. The focus is on risk management strategies, planning, assessment, and review. The objective is to monitor, review and adapt to ensure the strategy and objectives of the organisation are still valid for addressing the needs of its internal and external stakeholders.

3.3. Comments supporting countries' results

Based on analysis of the documentation the comments below provide some reasoning behind the selection results. These comments are not infallible but were investigated from the currently available guidelines and government documentation which is in itself an indication of available instruction to users and producers. The countries of this study's focus were identified based on those who are most active in the research space, have developed biosolids management plans and included representation from the major world regions. The research space perspective was considered a valuable component as it indicated the country was endeavouring to employ progressive technology. Furthermore, their wastewater treatment plants (WWTP) managed both domestic and industrial sources either directly or indirectly i.e., some pre-treatment may have been required before accessing the WWTP. It should be noted at this point the term "sewage sludge" in the documents analysed was used interchangeably with the term biosolids across several nations most notably the EU, China, and Japan. In the USA the term "sewage sludge" refers to all solid, semisolid, or liquid leftover from domestic wastewater treatment whereas biosolids refer to a product that can be recycled and meets the land-application standards (Pepper and Gerba, 2009).

3.3.1. Australia

Australia controls its quality for biosolids through a system of end-point limits and the Precautionary principle using the lowest observed adverse effect concentration (LOAEC). The selection results applied for adherence to the Australian documentation complying with the standards components identified in Tables S1 and S2 were based on averages across the states. Although some states may be fulfilling the requirements of the criteria others are lacking definition in their individual current biosolids guidelines. For example, Victorian guidelines include a Hazard analysis critical control point (HACCP) whereas the other states did not. Most other states had source identification but had not consistently applied these at their wastewater treatment plants and without a defined management plan. As the source was considered this was recognized as a single component under the HACCP category. Implementation and performance evaluation were both inconsistent across the states and hence not recognized as being fully applied. Risk assessment was identified as part of all guidelines although many features around risk management were not present or inconsistently applied. What seemed to need further development was a consistent management plan around risk.

3.3.2. New Zealand

New Zealand currently controls its quality for biosolids through a system of end-point limits and the Precautionary principle using the lowest observed adverse effect concentration (LOAEC). The guidelines contained most of the criteria identified by the mapped standards hence many of the criteria were acknowledged as present. The exceptions included emergency operations under implementation operations, and resource allocation under implementation support. These elements were awarded two dots as many items such as planning and quality control were well documented. Additionally, risk uncertainty would have benefited from more detail around the risk scope, risk-based decisions and transparency of action and decisions with the use of uncertainty.

3.3.3. USA

Quality, environmental management systems and the Hazard Analysis Critical Control Point (HACCP) were present in the National Biosolids Partnership guidance documents. Quality is controlled using end-point limits but unlike those countries that control contaminants through the precautionary principle where the LOAEC limits are derived through laboratory trials, the US EPA rule 503 uses maximum allowable concentrations established through cumulative loading rates established by risk assessment. Exposure pathways are also evaluated using risk assessment but not all pathways appear to be regulated. The pathways not adequately evaluated in 1993 Part 503 include inhalation, surface-water contamination by runoff, groundwater contamination and secondary transmission of disease (National Research Council, 2002; US EPA, 2011). The defined attributes under quality, environmental management, and the sludge recovery, recycling, treatment, and disposal standards showed comprehensive coverage in the biosolids management plan documents analysed. The areas needing more definition under risk were the risk management categories of risk implementation for decision-making and its transparency, the risk scope management activities and risk treatment plans.

3.3.4. Canada

Most of the elements of the quality, environmental management, and sludge recovery, recycling, treatment, and disposal standards were identified in the 3 guidelines and their accompanying 3 technical manuals. The exceptions were there was source control for quality control but no HACCP. Although Ontario Water had a HACCP system installed for drinking water it was not present concerning biosolids. Like Australia, New Zealand and Europe, Canada uses the precautionary principle regarding contaminant control. The explanation of the biosolids classification framework was brief and needed more detail around restrictions for use Otherwise, the documentation examined indicates that the Canadian biosolids framework displayed a comprehensive coverage for all risk criteria and all other components of the standards.

3.3.5. UK

The Biosolids Assurance scheme (BAS) and Hazard Analysis Critical Control point (HACCP) framework contained elements of the quality management system but no environmental management system. There was no defined biosolids classification framework identified in the three guide documents although there was a categorization of the sludge source. Otherwise as indicated in Table 3 the UK was mostly well covered for risk although there was no definition around the scope of risk activities and their level of application e.g., strategic, operational program or project.

3.3.6. EU Ireland

The larger EU was not selected for this analysis as there is a large variation regionally and considering the differences geopolitically, historically, and financially. Therefore, each of the member countries should be judged on its circumstances. Collivignarelli et al. (2019) demonstrated the diversity of sewage sludge management across the EU. The EU advocates for the precautionary principle in its current directive for controlling "sewage sludge", (EEC, 1986; Gianico et al., 2021). This principle was in existence in several of the countries in this study. Details of the EU's sludge directives relating to sewage sludge are documented in Tables S6 and S8. The Republic of Ireland comes under the EU Sewage Sludge Directive (86/278/EEC) which regulates endpoint limits and applies the precautionary principle. Implementation of this directive as with all EU member states has been actioned through national legislation (Schowanek et al., 2004). Hence, this became part of Irish law in 1998 by the Waste Management (Use of Sewage Sludge in Agriculture) regulations and was amended in 2001. The current guidelines for biosolids application in Ireland apply some elements of quality management but no environmental management systems. The guidance on implementation lacked detail on resource allocation, stakeholder communication, documentation, and emergency action. There was no Hazard Analysis Critical Control Point strategy nor could a biosolids management framework be located, although as part of the licence agreements, there is a requirement for pathogen testing before release. In the guidelines, the benefits of biosolids needed more definition and economics were not addressed. Disposal has been updated in the EU legislation since the 1998 guideline was developed, so this document needed an update. Risk although acknowledged needed a strategy and framework to produce a more comprehensive result.

3.3.7. Japan

There were many elements identified in the literature for a quality management system, and end-point limits were enforced through regulation, but no environmental management system or Hazard Analysis Critical Control Point strategy was identified. If there was no apparent evidence of source control. There are no formal biosolids guidelines although government priorities were defined through their ministry media releases so, context and leadership are apparent with a focus on circular economy. The planning lacked detail concerning risk management strategies although the risk was acknowledged. Implementation areas of competence, awareness and documentation were not clearly documented in the documents viewed. As economics and benefits were well covered and quality control and environmental control have a system-wide approach so were considered comprehensively addressed. Although performance evaluation and improvement were not discussed in those terms there was substantial documentation and policy around the circular economy framework focusing on a sustainable sound material society incentivized in business models, products, and services so was considered comprehensive in their management. Risk management strategies were not identified in any of the government documentation although the concept of risk was acknowledged.

3.3.8. China

China applies regulated end-point limits for waste, and although there was no specific documentation for environmental, quality management systems, or the sludge recovery, recycling, treatment, and disposal of biosolids many of their elements appear to have limited coverage in the Five-Year Plans. There was no mention of a Hazard Analysis Critical Control Point management (HACCP) strategy or a biosolids classification framework (BCF) and sewage sludge quality was documented as being managed through end-point limits identified in the China national standards (Ge et al., 2019). HACCP was present in the form of source control but no biosolids classification framework was apparent from the documentation. Implementation areas of competence and awareness were not addressed, and operations control was conducted through a bidding process so more financially driven. This process was considered unlikely to facilitate the promotion and implementation of sustainability policies. Documentation was around wastewater and not biosolids specific. These elements were not identified from the searches for implementation, support and operations. A risk management strategy for biosolids was not apparent from the government documentation or through the research papers examined. The risk was acknowledged for planning in the 13th and 14th Five-Year Plans and briefly about establishing a mechanism for monitoring and management with most comments around compensation and investment. Environmental risk was encouraged but no defined plans were discussed.

4. Discussion

4.1. Comments on guidelines resilience

There were substantial variations between the countries based on the criteria identified. Based on the analysis of the guidelines and mapped standards displayed in Table 3 Canada, NZ, USA, and the UK appear to have a high resilience built into their biosolids management plans. This result is largely due to the presence of a risk management program but also their planning and evaluation programs are more consistent with the international standards. The USA guidelines and documents relating to biosolids management were the most comprehensive and hence considered to have high resilience under the QMS, EMS and SSRD standards. Under the risk implementation plan criteria for ISO 31000, the details for decision-making and modification mechanisms were documented but not for decisions involving risk activities. Additionally, how these were to be applied to the various stakeholders was not described. Australia shows moderate resilience but lacks a consistent risk management program. Japan and China although featuring strong leadership, their resilience is moderately low. This is likely due to implementation mostly around resource support, communication, community engagement, documentation, quality classification criterion, and risk design. The Republic of Ireland's low resilience was a consequence of several issues, most specifically a biosolids classification framework, a risk management implementation strategy, and resource support. These items were either lacking or not evident in the biosolids management guides. The low resilience could be viewed as justified when considering the result in 2019 when the EU declared the Republic of Ireland non-compliant under the Urban Wastewater Treatment Directive due to failure to meet the minimum criteria for discharges from wastewater treatment plants in several major cities (EPA Ireland, 2019). While the non-compliance was related to effluent quality rather than a risk management framework it is a reasonable assertion that improved risk management activities could lead to improved effluent quality.

4.2. Regulatory frameworks: similar pathways with differing objectives

4.2.1. Frameworks evolution

Regulatory frameworks underpin all management framework strategies across the countries studied see Tables S4, S5 and S6. The US EPA sludge management framework, 40 CFR Part 503 developed in 1993 under the direction of the Clean Water Act (CWA) and provided pollutant guidelines for the USA National Water Quality Framework (US EPA, 2021b). The CWA directs the EPA to conduct biosolids biennial reviews to assess new contaminant identification, and the US EPA regulations for control within the compliance framework of the CWA (US EPA, 2021a). The USA, EU, Canada, the UK, New Zealand, Australia, Japan, and China all followed a similar development strategy for their biosolids management plans. Initially, there was the establishment of a law to regulate activities and controls set in place to maintain minimum standards see Tables S7 and S8 followed by management frameworks and guidelines on how and under what conditions the laws apply. Among the challenges for guidelines and legislation is their need to be consistent. Management frameworks and guidelines can lag the regulatory frameworks and sometimes vice versa. An example of this was found in the Australian state of Victoria, where the Public Health and Wellbeing Act of 2008 and the Environment Protection Act of 2017 postdate the 2004 Victorian EPA Guidelines for Environmental Management - Biosolids Land Application publication. Those acts set the standards for the safe management of biosolids. The Australian states of New South Wales, Victoria, Western Australia, the Northern Territory, and the Australian Capital Territory all have guidelines that predate the current legislation while Queensland, South Australia, and Tasmania are covered by current legislation. Another example of significance was the passing of the Hazardous Chemicals and Fertilizer Acts of 1985 (although the Fertilizer Act, of 1985 was subsequently replaced by the Biosecurity Act 2015) which was not acknowledged in the 1997 New South Wales Guidelines for Biosolids Management. For consistent benefit, these guidelines ideally need to keep abreast of regulatory changes.

4.2.2. Alternative approaches

The regulated controls for contaminants in New Zealand, Australia, and the European Union operate under the Lowest Observed Adverse Effect Concentration (EEC, 1986) with end-point limits. Although management tools and legislation for biosolids across countries have differing aspects of priority the flow of ideas occurs internationally. An example of this was using the European Union Industrial Emissions Directive (IED) and the OECD Best Available Techniques and Technologies (BATT) (EC, 2008, 2010) rationale providing insights for application in Australia's Victorian Environmental Protection Act 2017 (Victorian Government, 2017). Australasia, Ireland, China, and Japan operate their contaminant control via endpoint limits. The USA and the UK operate their controls via a HACCP system. Canada operates a hybrid system that supports a source control program and applies regulated end-point limits.

In Japan primary policies which govern biosolids and their application include the Sewerage Law 2015 (JSWA, 2020), the Johkasou Law 1983, the Waste Management Act and Public Cleaning Law 2010 (ADB, 2016; Umeda, 2020) and the Fertiliser Regulation Act 1971 (Kumazawa, 1997) amended 2019. This government's strategies differ from other countries by having a more voluntary approach to negotiation with stakeholders. This light-handed approach (quantity and quality controls, negotiation and voluntary action) was estimated to be the most cost and result effective particularly when the number of stakeholders is large (Arimura et al., 2019). This is still the case despite the existence of strong environmental policies and action plans. The management style is also applied at the project level. Although the national rules and regulations relate to projects around sanitation and wastewater management, the success of project implementation lies with local governments. An effective cost-sharing arrangement with government subsidies and a transparent stakeholder consensus-building process has been implemented successfully (ADB, 2016). Japan's waste management focuses on the circular economy, which follows the Japanese philosophy of Mottainai (Hotta, 2013; MOE, 2013). As a consequence of limited available land the disposal of sludge by incineration (JSWA, 2020) has dominated policy and management plans. In Japan and China the adoption of incineration to manage sewage sludge and municipal solid waste is widespread and in the case of China, is rising (Christodoulou and Stamatelatou, 2016; Ding et al., 2021; Mian et al., 2016; Wei et al., 2020; Zhao et al., 2022). The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has had the responsibility for the incineration of sludge managed within the centralized systems while managing the centralized sewerage system for the municipality and prefecture. The Ministry of the Environment (MOE) solely manages the decentralized wastewater treatment system (Johkasou), community and night soil plants. The Ministry of Agriculture, Forestry and Fisheries (MAFF) manage the rural sewerage system (ADB, 2016). The Johkasou practice conducted in rural or peri-rural areas provides a sewerage system for difficult-to-access regions but given the difficulty of managing control of these contaminants, this practice may have limited time use left.

Similarly, China supports a centralized sludge incineration and processing system (China Govt, 2021). The rural experience does not focus on decentralization like in Japan but on the centralized wastewater treatment to facilitate the recovery of untapped biomass waste with the 2030 aim of having zero agricultural waste (Li et al., 2021). China's 13th Five-Year Plan focuses on pollution volume controls and targets, the safe treatment and disposal of sludge from sewage treatment plants and the prevention of secondary pollution (Xiaoxin et al., 2019). The main sludge management options used are currently sanitary landfills, incineration, construction materials, and agriculture. The type used is dependent on regional economic conditions, urbanisation rates, land, and finances available. Among other management options, incineration is rising in response to its ability to control contaminants. The concern with incineration is the management of CO_2-eq emissions (Wei et al., 2020). The recommended management options for sewage sludge applications include testing, and background contaminant concentration controls (Chu and He, 2021). There are plans to build pilot projects for local small-scale domestic waste incineration facilities to assist with municipal sewage treatment (China Govt, 2021). These policies reflect strong leadership and direction although the translation at the province level has been more of a challenge as there is extensive flexibility at the local People's Congresses and governments level (Bao et al., 2021). Articles on the effect of policy on pollution in China recognise some improvements in areas where there is stricter adherence to the legislation but there is a lag effect on the response which includes biosolids (Bao et al., 2021). The Chinese Government's 13th Five-Year Plan focused on increased coverage of sewage treatment across urban areas. It also acknowledged the severe water shortages, which led to water recycling which was seen as an effective means to supplement supply. Thereby investment into these projects was encouraged for the domestic sewage treatment industry. Operating modes used to facilitate this included both private and private-public contracts. An example of the private-public type included a cooperative risk and benefit-sharing arrangement with the application of a Private, Public Partnership (PPP) contract (Fu, 2020). This may lead to a less-than-ideal situation for the broader environment and community if the interests of neighbouring communities are not engaged in the design process.

4.2.3. Comparison approach

The general observation during the analysis was that biosolids management guidelines do not include risk management even in the same jurisdictions where the drinking water guidelines do. The drinking water guidelines (ADWG, 2022) have come a long way particularly concerning risk management. We can learn something from them and apply it to biosolids. This imbalance was initially identified by public concern in the USA in 2002 and acted on by the US EPA in a review of the procedures of their Part 503 rule. Further studies continued with risk modelling work in the decade after (Eisenberg et al., 2008). Risk management is still an area of development in the USA's biosolids guidelines. The Australian national biosolids guidelines cover classification, contaminants, monitoring and regulatory controls with some elements of quality and environmental management but no risk management plan (Australian Govt, 1997; NRMMC, 2004a, 2004b). Within Australia, the states provide their own interpreted biosolids guidelines and some have begun to introduce risk management concepts (Darvodelsky, 2012) e.g., the NSW EPA is in the process of redesigning their Biosolids guidelines and drawing from the risk-based approach currently existing in the Australian drinking water guidelines (Randall et al., 2020). Contaminants such as microplastics and PFAS are still being identified in the terrestrial environments from the recycling of biosolids while also being detected in drinking water (Harley-Nyang et al., 2022; Hatinoğlu and Sanin, 2021; Koelmans et al., 2022). Hence the method of dispersion for these contaminants is being discussed currently so biosolids management risk strategies need to be cognizant of the potential risks around these sources (Pepper et al., 2023).

4.3. International goals of the UN, WHO, OECD, ISO, and their application nationally

The UN, WHO, OECD, countries, states, provinces, regions, or jurisdictions all have a measure of influence over the management of biosolids. Although not all countries are signatories to these organisations, it does not mean their influence is not felt at all government and industry levels. The International Institute for Applied Systems Analysis and the UN-sponsored Sustainable Development Solutions Network, are both examples of organisations that support the achievement of these international goals (Schmidt-Traub et al., 2019; TWI 2050, 2018). Understandably, a clean water, management strategy has been prioritised by these organisations. Given their importance as thought leaders, however, greater emphasis on the risks and benefits of biosolids is likely to pay dividends. Raising awareness through industry bodies will also highlight their importance.

4.3.1. UN's sustainability goals and biosolids

The SDGs of most significance for biosolids are SDG 6 the sustainable management of water and sanitation, SDG 11 for safe, resilient, and sustainable human settlements, SDG 2.3 and SDG 2.4 relating to sustainable agriculture and SDG 3.3 and SDG 3.9 relating to reducing waterborne disease. Research since 2015 has increased its focus on sustainable solutions in response to the need for pollutant control and global responsibility targets (Aldieri et al., 2019; Allen et al., 2016). Indications are that the SGD 2, and 3 goals are not being successfully met and thus require greater attention.

Getting contaminants below a certain level and achieving the specified degrees of stabilisation to reduce odour and pathogens at highly regulated wastewater treatment plants are some of the prominent actions effective biosolids management can contribute to the SDG goals (Irwin et al., 2017; Mohajerani and Karabatak, 2020; Moya et al., 2019). Other important ways to achieve the sustainability goals with biosolids are by the considered management of treatments and production and their effect on carbon footprints. The most sustainable, and technically mature treatment of biosolids includes digestion and drying technologies. While the emerging sustainable technologies being applied to the biosolids to improve resource recovery while managing the product are fit for purpose e.g., thermal hydrolysis and cold plasma technology (Kanteraki et al., 2022). Another developing sustainable technology for the treatment of biosolids adding value to the circular economy is pyrolysis (Rathnayake et al., 2022; Shah et al., 2022). Assisting from a strategy perspective is the use of scenario modelling and analysis for policy and investment decisions (Allen et al., 2016; Allen et al., 2021). Most national strategies for biosolids management depend on operations and cost benefits analyses (LeBlanc et al., 2008b, pg 71; LeBlanc et al., 2008a, pg 8; Tchobanoglous and Leverenz, 2019, pg 2). Furthermore, there is a need for clear policies, with institutional engagement and social acceptance for the development of a pathway to sustainability (Moya et al., 2019). Similarly, a risk management strategy working more cooperatively with the local community and industry is expected to lead to more achievable solutions. Risk tolerance levels for both are hence recommended to be part of the framework as one solution does not fit all scenarios.

4.3.2. UN's lead on contaminants and biosolids

The UN lead on contaminants is guided by the Stockholm Convention on Persistent Organic Pollutants (POPs) (UN, 2017; United Nations, 2016). It is a reasonable assumption that all countries with water and wastewater facilities would be cognizant of these hazardous contaminants, as the information is in the public domain. POPs, routinely identified in the sludge management guidelines of this study included metals, metalloid arsenic, and organochlorine pesticides. These recommend both regular and intermittent monitoring of select compounds identified under the UN Stockholm Convention. The EU regulation of 2019 has regulated these concerning source management and monitoring (EU, 2019). One point of note was the US EPA in 2001 established that dioxin-like compounds disposed of by incineration or land-fill were not a significant risk to human health or the environment and so in 2003 confirmed they did not require regulation (US EPA, 2006, 2018). Limited databases of the WHO_UNEP for dioxin-like compounds restricted the application of the risk assessments as described by Van Den Berg et al., (van den Berg et al., 2013). It was noted in the 2010 US EPA biennial review the RMS models were not working as they were not getting the required data support which provided the impetus for further work in later reviews (US EPA, 2010). In the USA biosolids biennial review it was documented that monitoring of dioxins and furans was ongoing, although not the organochloride insecticides, Mirex or Endrin (US EPA, 2021a) as recommended by the Stockholm Convention on POPs. In all other biosolids guidelines included in this study Dioxins, Furans, Mirex and Endrin were not identified for monitoring. In the EU, like the USA, not all POPs have threshold limits in the guidelines as they were determined not to present a significant risk, but monitoring has been maintained to collect more data (Clarke and Cummins, 2015; EC, 2012). Additionally, in 2019 it was determined for fertilizing materials that incineration with stable combustion conditions acceptable level of POPs can be achieved with no unburnt residue (Huygens et al., 2019).

4.3.3. Comments on standards applications

The application of the standards in the biosolids framework, management and environmental documents in this study have been inconsistent across the frameworks in place. ISO 9001 (QMS) has been most consistently applied although not acknowledged where reference was made to ISO 14001 (EMS) with most items recorded. The PDCA was used in the development of ISO 14001 and ISO 9001.

The USA's National Biosolids Partnership's (NBP's) Biosolids Management Plan (BMP) manuals were made with reference to the QMS, EMS and PDCA and these were adhered to rigorously. No reference was made to ISO 19698 (SRRTD), but all its items were covered in NBP manuals and guidelines. The NBP's BMP consisted of a practice guide and manual (NBP, 2011a, 2011b) developed in 2001 and was updated in 2011. The NBP's purpose was to assist wastewater organisations with the management of public health and environmental objectives to achieve sustainable outcomes. This independent, non-government federally funded collaborative program consisted of the U.S. Environmental Protection Agency (US EPA), the National Association of Clean Water Agencies (NACWA) and the Water Environment Federation (WEF). This organisation as of 2013 was currently operated by the WEF solely. Like the ISOs, the BMP principles use the widely used process template for continual improvement, the PDCA.

Canada's guidance documents adhered to the same standards although no mention of the ISO standards was made in the documents. The UK Biosolids Assurance Scheme guidelines reference no standards but contain all items for the QMS, but no EMS planning or sustainability program was discussed. The Republic of Ireland did not apply the QMS, EMS or SRRTD standards but acknowledged a requirement for these to be developed. China, although not acknowledging the ISO standards in the government documents examined, do apply standards through the Standardization Administration of the People's Republic of China (SAC).

Two of these specifically related to biosolids are GB 18918-2002 for raw, treated sludge cake discharge standards and the control of pollutants in sludge when applying to agricultural land GB 4284-2018. China also uses their own standards for environmental, quality and risk management. Japan has also developed their own standards through the Japanese Industrial Standards (JIS) and although they appear to have no general sludge management standard for the environment, quality, and risk standards, they follow the principles of the ISO standards. Based on searches of China's and Japan's government documents and research articles it was apparent substantial effort had been made towards the ideals of the circular economy and the application of the ISO standard's elements had mostly been addressed. The 14th Five-Year Plan follows the 13th by focusing on green development, reduction of carbon intensity and peak carbon emissions before 2030 to be carbon neutral by 2060. Additionally, these Five-Year plans support circularity in agriculture through the development of a National Sustainable Agriculture Development Plan (Li et al., 2021). Like Japan China embraces circularity. Li et al. (2021) suggested improvement would come through improved efficiencies of the natural resources and increased investment. However, there was no apparent document that fully translated these standards into practice in the form of guidelines.

4.4. Quality control and long-term application

The analyses presented in Table 3 identify features such as effective policy, frameworks, and standards as essential components in the development of a quality biosolids product. Identifying end uses and tailoring the treatment to be fit for purpose is a necessary step to enable product commercialisation and ensure a sustainable outcome.

4.4.1. Sustainable land application

Biosolids are recognized for their values in terms of plant growth and soil conditioning. Sustainable beneficial land application has been managed through government guidelines defining the rules of best practice. The sustainability practices commonly used in the application of biosolids are loading rates and contaminant limits. The controls for the application and repeat application of biosolids were described by Stevens et al. (2012). They demonstrated the successful repeat application of biosolids to land with an average annual target greater than 100 % to address current stockpiles. They also compared the general guideline rules supported by regulations covering repeat applications in Australia, Canada, the USA, New Zealand, and the UK. The variances they identified were mostly around the measurement of loading rates and contaminant limits both pre-application and in the biosolids being applied. The recommendations were similar to those stated by Smith (2008) to use a national risk assessment process to manage the land application of biosolids. Despite the assurances of the safety and benefits of using biosolids in agriculture, there have been different levels of acceptance which have led to an increase in the use of incineration (Smith, 2008). The standout issue around this strategy is balancing the loss of nutrient quality and the safety of the product. The importance of Risk assessment and management controls include a multi-barrier approach, regulations, and practice standards, to address issues of confidence around the use of biosolids (Smith, 2008). Effective management strategies supporting sustainability have been proposed for the water and wastewater sectors and highlight the need for clear policies, with institutional engagement and social acceptance (Holley and Sinclair, 2016; Moya et al., 2019). These elements it is envisioned will be subordinate to the risk framework to enable a comprehensive flexible system to operate.

4.4.2. Contaminants in biosolids

The long-term benefits of biosolids applications have been reported particularly concerning depleted soils (Brown et al., 2011; Ippolito et al., 2021). Placing a caveat on these successes are the studies that highlight the risk of micropollutants such as microplastics, PPCPs, PFAS, PAHs and metallic trace elements. It has been demonstrated these contaminants are poorly eliminated by anaerobic digestion (AD) with current pre and post-processing techniques, and contaminants can make their way into the food chain with a persistent, accumulative, and toxic potential (Dubey et al., 2021; Ghirardini and Verlicchi, 2019; Venegas et al., 2021). Points of note include; the nutrient value does vary significantly with the source material and AD operation (Chen et al., 2021; Fischer et al., 2020), and its value is impacted by the thermal treatments so pre-processing recovery is a means to address this deficit (Marchuk et al., 2023). Incineration in China and the EU has increased in favour in recent years for their sludge management despite the costs (Raheem et al., 2018; Zhao et al., 2023). In China, AD compared to direct incineration was measured to have higher energy, operational and investment costs (Hao et al., 2020) despite incineration having the additional drawback of enhanced CO_2 emissions (Pepper et al., 2023), and CO_2eq production from AD being minimal compared to incineration (Brown et al., 2010). These features were compared holistically by Lee et al. (2020) in a life cycle cost analysis (LCCA) study of medium and large WWTPs and by Zhou et al. (2020) using a multi-criterion decision-making method (MCDM) method using China and EU data where AD was identified as the most cost-effective solution. Circumstances including sludge sources, economy, temporal conditions, and challenges will be part of the solution for a best-fit design (Raheem et al., 2018).

Research has revolved around the recognition and detection of PFAS contaminants (Bolan et al., 2021) and detection in human populations (Thompson et al., 2011). Following up on this work the OECD completed a risk reduction analysis (OECD, 2015). In Australia, the first PFAS national environment management plan (NEMP) was developed in 2018 with the aid of international standards and the Stockholm Convention on POPs (HEPA, 2018). The first revision NEMP 2.0 (HEPA, 2020), focused on environmental guideline values, soil reuse, wastewater management and on-site containment, the second revision draft NEMP 3.0 which focuses on biosolids was released in September 2022, with public consultation closing in February 2023. Plans currently under development are still being monitored and matched with ongoing research (Bolan et al., 2021; Hall et al., 2020; Umeh et al., 2021). The US EPA has an ongoing action plan till 2024 to address PFAS contaminants (US EPA, 2021c) and is continuing to monitor new PFAS threats (US EPA, 2022). However, much of the regulation in the US is state-based and different states will have different approaches to managing PFAS for example, in 2019 Maine implemented a moratorium on biosolids recycling with the requirement to test all biosolids products prior to any future application to land (Beecher, 2019). Factors affecting the concentrations in the soils of PFAS include a combination of the biosolids wastewater source, groundwater leaching, soil depth, biosolids and compost loading rates, plant uptake and local climatic conditions (Bolan et al., 2021; Pepper et al., 2021).

Microplastics' presence in the terrestrial environment has also become more detectable and the risks posed to human health raise questions from the public, water companies and regulators (Harley-Nyang et al., 2022; Hatinoğlu and Sanin, 2021; Koelmans et al., 2019). The consequences of these contaminants in the environment have been elevated by the fact they can be cumulative while also having the detrimental effect of increasing the accumulation of other micropollutants like heavy metals (Mohajerani and Karabatak, 2020). In addition to their persistent nature, microplastics are ubiquitous and evolving most specifically to smaller particle sizes and increasing bioavailability hence a potentially more invasive effect on the environment. Risk management for these contaminants needs to account for a timeline of risks to understand what is coming in terms of exposure and effect (Koelmans et al., 2022). The regulation around microplastics does not have the same emphasis as PFAS currently despite its apparent broader exposure.

Treatment and plans to control have been effective for the contaminants that are known but it is the newly identified where the risk is not quantified that pose a challenge. Early intervention management strategies for emerging contaminants such as PFAS include source control, elimination and minimisation strategies (EGLE, 2021). More medium-term strategies to address these contaminants include continuous investigation for changes in the environment, local anthropogenic conditions, and human health.

4.4.3. Groundwater and trans boundaries

Groundwater can be an effective conduit for wastewater with transmission through unconfined aquifers as evidenced by the elevated ion content (Foppen et al., 2020). The potential for contamination of groundwater from biosolids has been explored by Pepper et al., (Pepper et al., 2023). Aquifer transmission of contaminants may produce pollution problems for neighbouring properties or countries. Transboundary cooperation is necessary for the management of wastewater. In Ireland, there are multiple transboundary groundwater bodies previously managed through the EU water framework directive. The 91/271/EEC Urban Wastewater directive does provide 60 % protection with regard to transboundary water basins from wastewater discharges (EC, 2019). A post-Brexit decision is yet to be made as to whether the status quo will continue, or an agreement will be made between the countries. The agreement will help with resource management, water quality and SDG targets (Fraser et al., 2020). That being the case biosolids usage needs to continue to be as part of any new agreement and regulations ensuing. Aquifer modelling may assist with the management of situations that cover biosolids and groundwater. For example, using the US EPA-developed risk characterization screening tool to assist with decision-making has improved the understanding of the impact of biosolids applications and implications for human health risks (McFarland et al., 2013).

4.5. Risk strategy development

The US EPA Part 503 Rule contains a comprehensive risk assessment and management process (US EPA, 1995). Components of this Standard form the basis of the international risk management standard, ISO 31000:2018 (ISO, 2018). These include general requirements, reporting, monitoring, management practices and operational standards. However, elements are missing from the US EPA risk management documents such as those around design, planning and community engagement (see Table S10).

The EU structured their Sludge Directive 86/278/EEC in 1986, which despite undergoing re-evaluation in 2021 remains in effect (Gianico et al., 2021). Additionally, although it gives directions on sludge management and limits for heavy metals it does not contain a risk management framework. Risk-based methodologies have been proposed for the EU, but are yet to be implemented (Schowanek et al., 2004). In the UK the risk assessment and management process has been developed under the guidance of the Biosolids Assurance Scheme (BAS, 2020). The UK, Canada, and New Zealand each have biosolids guidelines with risk management frameworks that cover most of the ISO 31000 criteria whereas Japan and China although monitoring their contaminants, from appearances have no risk management or biosolids classification frameworks in place (see Tables S9 and S10).

Research over the past 20 years has focused on contaminants present in biosolids and the risks they present (Gerba et al., 2002; Rigby et al., 2021; Smith and Riddell-Black, 2007). USA developed the quantitative risk assessment model (QRMA) in the food and water industries in the 1990s (Buchanan and Whiting, 1996). In 2002 it was used to understand the risk of land application biosolids on multiple levels, including infection, illness and mortality (Gerba et al., 2002). This study examined contaminant exposure, occurrence, and fate and then estimated risk outcomes probabilistically. In Europe in 2004 a conceptual framework for the application of sludge in agriculture using risk as the focus was created. This EU-focused study defined sludge, regulatory controls, pre and main treatments, disposal, quality controls and exposure pathways, followed up by an examination of the risk endpoints for the environment and public health. The validity of the framework was based on the repeat regime assessing accumulation with a mass balance at set time intervals (Schowanek et al., 2004). In the USA at this time models were also applying a risk assessment methodology to assess microbial health risks and biosolids scenario (event) analysis (Brooks et al., 2005; Eisenberg et al., 2004). This work was followed by a quantitative risk assessment process using a Bayesian structure to assess the risk incurred by exposure to microbial pathogens associated with biosolids applications (Eisenberg et al., 2006). A conceptual framework was then developed using a QRMA to understand the environmental exposure and risk to human health from metallic contaminants (Fairbrother et al., 2007). Eisenberg et al. (2008) broadened their risk assessment framework to evaluate the risk of exposure to pathogens from biosolids for human health using a Bayesian and quantitative probabilistic model. The Australian guideline for water recycling in 2006 set out a framework to manage the safety of water recycling schemes (NWQMS, 2006), using qualitative and quantitative risk assessment for the likelihood of infection and the burden of disease using a maximum target risk using a metric, the disability-adjusted life year (DALY). More recently in 2021, QRMA and the DALY metric standard were used to translate pathogen levels into a health risk and for water recycling efficiency (Owens et al., 2021). Bayesian modelling has progressed with the science of probability combined with the probabilistic risk assessment process in the hazard risk assessment (Bodda et al., 2020; Kwag et al., 2018; Kwag and Gupta, 2017). The risk assessment on a regional scope applying probabilistic modelling to biosolids is also being developed (Nag et al., 2022). This methodology of probabilistic regional modelling needs to be set up on a regional scale for the PFAS and other contaminants. Risk measurement and modelling will improve the industry's ability to fully take advantage of the biosolids resource.

4.6. The gaps in global biosolids management

While the insight gained by the standards mapping revealed extensive overlap between the more commonly applied quality (QMS) and environmental (EMS) standards with the risk standard at the heading level, the detailed perspectives were very different. In addition for most countries reviewed the experience of developing and putting these strategies into practice has been better executed for quality and environment than for risk. The review of the framework's evolution may provide some understanding of this observation. For many countries, the initial response to the need to manage biosolids was to enact laws to regulate them followed by the establishment of quality standards. Therefore the quality standard has the broadest global implementation. Guideline attributes across the QMS, EMS and SRRDT categories of support, resources, quality control and operations, and the risk categories of uncertainty, planning and decision-making have been less widely implemented. A limitation of the method used to produce Table 3 is that it did not account for the level of detail provided in the guideline documents. For example, two or more countries that are fully compliant with a feature attribute may also have a large difference in the level of detail applied. One set of guidelines may comprehensively incorporate many aspects of a risk management framework whereas another may apply these aspects in a more limited way. Thus Table 3 indicates only the absence or presence of the components rather than the degree of their development. Guidelines that do not capture the full suite of vulnerabilities by not basing their view on the full risk profile may miss areas of need and opportunity. The tools that have significant potential to add value in this space are the burgeoning life cycle analysis studies which focus on consequences for the end-user, cost and social and environmental impact. Although these models provide measurements and general priority to certain goals these need to be applied under the umbrella of a total risk scenario profile.

Source control has been widely implemented in many jurisdictions as a key approach to contaminant control. Taking this concept further to create a system of multiple, overlapping checks may further reduce the risk of unsafe contaminant exposure. This can be realized by implementing controls before, after and during the multiple steps of the production process with a range of testing parameters. This would also provide an opportunity for implementing mitigation strategies throughout the biosolids life cycle, at these control application points. These are likely to be where there is a change in the product at each process point and where the consequence of a poor outcome for health or the environment is possible. These HACCP strategies may be in place at some utilities, but being universally adopted has the potential to produce a more consistent, reliable, and auditable result. Furthermore, national approaches to the biosolids classification framework would assist with the transboundary movement of biosolids, allocation of resources and foster standardization of products.

The fate of contaminants is based on their mobility in the environment and how they are managed once dispersed through agriculture, incineration, emissions, and disposal of which biosolids play an integral role. The increased diversity of emerging contaminants, lack of a full understanding of their dispersion pathways and potential negative consequences have led to regulatory changes for biosolids which are driving an increased stringency in their management, reuse, and disposal. This has been experienced in all jurisdictions of this study. Despite this, the development of regulations and standards has often lagged behind scientific understanding of risks and consequences in the environment. Other considerations include appropriate implementation level (e.g., national, state, regional) and whether benefits gained from biosolids products have been negatively impacted by stringent regulations that may not be directly responding to identified risks. Furthermore, ongoing change associated with emerging contaminants has left many jurisdictions waiting for a clear path forward. While this is happening there is hesitance to commit to the update of guidelines and strategies. This and previous discussions highlight the multidimensional challenges of contaminants and global endeavours to measure, evaluate, and manage threats. A risk management framework enables decisions such as treatment requirements and contaminant limits to be aligned with local risk circumstances.

5. Conclusions

This study provided an assessment of the degree risk management frameworks have been adopted or recommended for biosolids management. A detailed analysis of guidelines in operation from eight countries is presented. This was followed by a review and comparison of broader issues around biosolids regulatory and management practices. Management guidelines for biosolids have broadly embraced the criteria of quality and environmental standards. For a few countries risk management concepts underpin biosolids management guidelines, although this has largely occurred over the last 10 to 15 years with some jurisdictions yet to adopt this perspective. The changing landscape with regard to emerging contaminants appears to have delayed further guideline development as this presents a moving target for regulation. However, the incorporation of a risk management framework would provide an adaptable basis for decision-making as technology and new data become available. It is this adjustment to the perspective that should underly the design of any new guideline upfront when developing the scope. Highly restrictive regulatory requirements, such as those based on specific contaminant limits, will not enable the flexibility to adjust quickly to changing scientific landscape, health, and environmental priorities.

CRediT authorship contribution statement

Marilyn F. Braine: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Matthew Kearnes:** Methodology, Supervision. **Stuart J. Khan:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

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Data availability

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Appendix A. Supplementary data

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