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Research article

Influence of policymakers and civil society stakeholders on sewage sludge management strategies: Empirical results from European utilities

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ABSTRACT

Sewage sludge management is crucial for water utilities to move towards a circular valorisation of resources. The current literature focuses mainly on the technological aspects of sludge management strategies. However, the current discussion of these strategies does not consider possible pressures arising from the utilities' civil society stakeholders and from policymakers. To fill this gap, this paper develops a conceptual framework, based on the current literature, that identifies the utility's key decisions on sludge management strategies (valorisation route, overperformance and vertical integration), and links them to possible pressures arising from civil society and existing regulations. Subsequently, the study validates the framework through a multiple explanatory case study, investigating the empirical relevance of such pressures in six water utilities across Europe. The influence of citizens and municipalities is found to be crucial in the choice of sludge valorisation routes. Economic instruments, command and control instruments and, new to the literature, regulatory uncertainty are found to be key policy features influencing utilities' decisions on sludge management. The paper provides a first-of-its-kind investigation that highlights the mechanisms through which policymakers and civil society stakeholders shape utilities' sewage sludge management strategies. The results complement and extend existing theoretical knowledge on the role of institutional pressures in the implementation of sustainable environmental systems.

1. Introduction

The pressure to move towards a circular economy and to increase the environmental sustainability of industrial systems has contributed to increasing attention to sewage sludge management in academic and managerial debates (Bagheri et al., 2023; Kathi et al., 2023). Sewage sludge is recognised as a source of resources for recycling and recovery, and therefore a valuable type of waste (Pasciucco et al., 2023). The availability of sewage sludge to be recycled or recovered is increasing worldwide (Siddiqui et al., 2023). Indeed, economic development and population growth are increasing the production of wastewater and the number of connections to wastewater treatment facilities (Di Fraia et al., 2018; OECD, 2024). The EU-27 countries are estimated to have produced between 6 and 9 million tonnes of dry sewage sludge per year since 2010 (Huygens et al., 2022). The average annual production of sewage sludge in the EU, the USA and China varies between 18 and 33 million tons (Semblante et al., 2016). Further, technological innovation and stringent environmental regulations are improving the quality of wastewater treatment processes (Caligan et al., 2022; van Loosdrecht and Brdjanovic, 2014), with less environmentally friendly options (such as landfilling) losing ground (Rorat et al., 2019). Therefore, the proper management of sewage sludge is a fundamental issue for the transition to a more sustainable economy, given the high possible benefits in terms of resource recovery and recycling, as well as the possibility of avoiding negative impacts on human health and the environment in terms of pollutant releases (Papa et al., 2017; Peccia and Westerhoff, 2015; Rorat et al., 2019; Tchobanoglous et al., 2014).

Most research into sludge management is concerned with the technological aspects of the process (Cieślik and Konieczka, 2017; Danish and Ozbakkaloglu, 2022; Świerczek et al., 2018; Wang et al., 2020a), neglecting the factors affecting the decision-making of the actors that should implement these processes (Tchobanoglous et al., 2014; Cagno et al., 2022) and adopt the related technologies. We focus on wastewater utilities (WWUs), which are, at least in the context of the EU and other high-income countries, pivotal actors responsible for wastewater treatment operations and sewage sludge management (Romano et al., 2016; Neri et al., 2024). The decisions on sludge management strategies of WWUs are inevitably influenced by several pressures from their external institutional environment (D'Amore et al., 2021). According to institutional theory (North, 1990), these can be divided into formal and informal institutions (Casson et al., 2010; Fuentelsaz et al., 2020).

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Abbreviations

CCI	Command and Control Instrument
CSS	Civil Society Stakeholder
EI	Economic Instrument
II	Information Instrument
WWU	Wastewater Utility

Formal institutions, i.e. authorities including supranational organisations, national and local governments, and courts (from now on referred to as *policymakers* for brevity) exert regulatory pressure against organisations through formal, written, and codified regulations (Aragón-Correa et al., 2020; Darnall et al., 2010; Mombeuil et al., 2023), while at the same time providing companies with economic incentives to pursue sustainable production patterns (Garrone et al., 2018a). Examples include zero waste programs (European Commission, 2019), waste hierarchy directives (Gharfalkar et al., 2015), economic incentives for utilities to minimise sludge landfilling (Guerrini and Manca, 2020). Informal institutions, i.e. citizens, non-governmental organisations, media (hereafter referred to as *civil society stakeholders* – for brevity, CSSs), exert normative pressures that require companies to adhere to a set of societal norms and expectations regarding their behaviour and decisions (Chen et al., 2018; Martinez, 2023; Mombeuil et al., 2023). Examples include contrasting pressures such as 'not in my backyard' movements (Garrone et al., 2018a) and activism for greater corporate sustainability (Mombeuil et al., 2023).[1]

The role of such pressures has been studied in previous literature on environmental innovation (Garrone et al., 2018b) and wastewater treatment (Garrone et al., 2018a), but further research is needed to understand how they shape decisions in the field of sewage sludge management. In addition to specifically addressing the pressures on WWUs in sewage sludge management, there is a need to empirically assess the mechanisms behind these pressures, while also understanding the interactions between formal and informal institutions. Furthermore, the voluntary adoption of environmentally friendly practices in sewage sludge management beyond what is required by existing regulations (so-called overperformance) is an untapped area of research, especially compared to other sectors where the determinants and effects of voluntary schemes have been studied (Cornelis, 2019; Evans et al., 2019). Finally, the most virtuous options for sludge management can be implemented through varying degrees of externalisation or, in contrast, through internalisation of the different technological and operational stages. Vertical integration in sewage sludge management, i.e. the control and operation of contiguous supply chain stages (Saal et al., 2013), has so far only been studied for specific utilities and countries (Abrate et al., 2017; Saal et al., 2013).

This study aims to gain insights into the decision-making processes of WWUs in sludge management and to understand how pressures from policymakers and CSSs shape and influence such decisions, particularly concerning sludge valorisation routes, overperformance and vertical integration decisions by WWUs. More specifically, the paper aims to answer the following research question: *How do policymakers and CSSs influence WWUs' decisions on sludge management strategies?* In answering the research question, the paper also aims to understand the possible interdependencies between the influence of CSSs and policymakers, as well as touncover the specific role that such influences play on the different decision levers of the utility, along with related mechanisms. To this end, we first develop through an analysis of current literature a conceptual framework that relates the key decisions by WWUs on sewage sludge management strategies (valorisation route, overperformance, vertical integration) to the possible pressures coming from institutions (policymakers and CSSs) and their mechanisms. We then empirically validate and refine this model through multiple explanatory case studies across six European WWUs. Our contribution is therefore a literature-based and empirically validated model that relates pressures coming from institutions to the key decisions in sewage sludge management, along with the underlying mechanisms. The framework sheds light on the nuanced and complex role of policy and societal pressures on WWUs' decision-making in sewage sludge management and offers therefore meaningful insights to WWUs, and institutional actors interested in influencing WWUs' decisions.

The rest of the paper is structured as follows. Section 2 presents the development of the conceptual framework. To do so, we focused our attention on the literature related to sewage sludge management strategies and the formal and informal institutions exerting pressures, i.e. policymakers (through the regulatory framework) and CSSs (through the stakeholder network). Section 3 details the method used for the empirical validation of the framework. Specifically, a multiple explanatory case study was conducted to provide an in-depth understanding and validation of the mechanisms by which policymakers and CSSs influence decisions in sludge management. Results are reported and discussed in section 4. After the presentation of the results, a discussion is offered to integrate our results within previous literature and frame them within institutional theory. We also highlight the main contributions and limitations. Section 5 finally reports conclusions.

2. Development of the conceptual framework

In this section, the conceptual framework is developed. First, a literature review is carried out on three main topics: i) sludge management strategies for WWUs (section 2.1, namely valorisation routes, overperformance, vertical integration); ii) identification and classification of the regulatory framework, and, in particular, of the policy instruments adopted by policymakers to influence WWUs' sludge management strategies and their related pressures (section 2.2, namely command and control instruments, economic instruments, information instruments, regulatory uncertainty); iii) identification and classification of the CSSs that form the stakeholders' network impacting on the sludge management strategies and their related pressures (section 2.3, namely citizens, municipality, farmers and land owners, non-governmental organisations and environmental activists, media, water associations). Finally, the framework is developed and discussed (section 2.4).

2.1. *Sludge management strategies*

According to the literature, we can identify three main sludge management strategies – namely valorisation route, overperformance and vertical integration.

2.1.1. *Valorisation routes and technologies*

Sludge valorisation routes are generally divided into recovery and disposal routes, with particular emphasis on sludge to energy, sludge to agriculture and sludge to material as recovery routes, and landfill as a disposal route (Aubain et al., 2002; Taron et al., 2023; Zhang et al., 2023). An overview of the above routes (i.e. landfill; sludge to agriculture; sludge to energy; sludge to material) is given here. For each route, the main processes are described, considering the main advantages and disadvantages. The processes discussed are largely based on the comprehensive review by Taron et al. (2023). Our interest in the present work is to understand the characteristics of the valorisation routes, not to deepen the understanding of specific processes and/or technologies, for which the reader can refer to the following recent and comprehensive reviews: sludge reduction technologies (Ferrentino et al., 2023;

[1] Both policymakers and CSSs (Cagno et al., 2018, 2022) are secondary stakeholders (Mitchell et al., 1997; Shubham et al., 2018) and therefore do not have direct economic relationships with WWUs.

Foladori et al., 2010); sludge to agriculture technologies (Colón et al., 2017; Corato, 2020; Zhang et al., 2023); sludge to energy technologies (Nkuna et al., 2024; Oladejo et al., 2019; Vatachi, 2019; Zaharioiu et al., 2021); sludge to material technologies (Gherghel et al., 2019; Kathi et al., 2023; Siddiqui et al., 2023). The following discussion is therefore organised by the valorisation route, which can then be implemented by WWUs through different specific technologies.

Landfilling is considered here as the worst option for sewage sludge management. The use of landfill is still widespread (Zaharioiu et al., 2021), and is mainly driven by economic reasons (Ye et al., 2022), as the landfilled sludge is usually not subjected to any treatment (Kacprzak et al., 2017). This option has drawbacks in terms of sludge stability and increased leachate production, as well as methane and carbon dioxide emissions (Kacprzak et al., 2017). In addition, landfilling means that recovery options are not exploited, and sludge is not valorised (Stunda-Zujeva et al., 2018).

Sewage sludge can be reused in *agriculture* (Aubain et al., 2002) either by direct application or after specific treatments (Hušek et al., 2022). Direct application of sewage sludge is rather widespread in Europe (Gherghel et al., 2019; Lamastra et al., 2018). Sludge is rich in nitrogen, phosphorous and potassium, making it an excellent fertilizer (Seleiman et al., 2020; Stunda-Zujeva et al., 2018; Ye et al., 2022). However, as agricultural applications only occur at certain times of the year and the sludge disposal rate cannot always be matched with the agronomic rate (Stunda-Zujeva et al., 2018), storage capacity for sludge is required. Repeated use of sludge as fertiliser may lead to the accumulation of harmful chemicals and pathogens, which may enter the food chain and endanger human health (Zhang et al., 2023). Indeed, the nutrient balance may not always be maintained, leading to eutrophication and over-fertilisation (Bora et al., 2020). In particular, over-fertilisation could damage the soil and the environment due to the presence of contaminants such as heavy metals (Nunes et al., 2021), phenolics, hydrocarbons, and grease (Lamastra et al., 2018), microplastics (Hušek et al., 2022; Zaharioiu et al., 2021) and sanitary contamination (Bolesta et al., 2022). In addition, there are concerns about the chemical and biological safety of crops grown with sludge, which are reflected in increasingly stringent regulations that limit the use of this option (Roig et al., 2012).

There are several treatments that may minimise the negative impacts of direct soil application (Colón et al., 2017). A first treatment is composting (Corato, 2020), which involves the biological decomposition and stabilisation of the organic substrate (Colón et al., 2017). During this process, the content of heavy metals is significantly reduced, as is the leaching of nitrates and pathogens. However, risks related to antibiotics, organic halogens or microplastics have been highlighted - for a complete overview of the risks associated with composting, see (Hušek et al., 2022). The process is relatively cheap, but with long processing times (Strande et al., 2014). Composting reduces the volume of the sludge, which has a positive impact on transportation costs (Colón et al., 2017). The local market demand for compost products should be carefully assessed (Strande et al., 2014). A second treatment is anaerobic digestion, which allows the simultaneous production of anaerobic digestate (biosolid), biogas and possibly biohydrogen (Corato, 2020; Nkuna et al., 2024). The biosolid contains nutrients for the soil but, depending on the quality of the treated sludge and the technologies used, it may also contain harmful compounds that pose a risk to human health (Corato, 2020). However, anaerobic digestion of sludge can stimulate the degradation of pharmaceutical compounds (Bolesta et al., 2022). Other treatment processes are then available, such as vermicomposting, bioleaching (Colón et al., 2017), aerobic stabilisation and lime composting (Buckwell and Nadeu, 2016).

The use of sludge in agriculture can also include the recovery of nutrients for use as fertiliser. Nutrients can be recovered from biochar (Bora et al., 2020; Taron et al., 2023) derived from the pyrolysis process (Hušek et al., 2022). In addition, ash from the mono-incineration process of sewage sludge can be used as a substrate for phosphorus recovery (Buckwell and Nadeu, 2016), while an ammonia-stripping process after the anaerobic digestion can lead to nitrogen recovery (Buckwell and Nadeu, 2016), and chemical precipitation during anaerobic digestion can allow phosphorous recovery (Zhang et al., 2023).

Sewage sludge can be managed for *energy* production. The organic content of the sludge allows its calorific value to be recovered (Hu et al., 2022; Strande et al., 2014). The thermal use of sewage sludge as a form of energy self-production is widely spread (Cieślik et al., 2015), as it involves large cost savings, possible profit from the sale of energy, and increased energy security (Strande et al., 2014). The main processes can be identified as follows: biological processes, namely anaerobic digestion, and thermochemical processes, namely incineration (mono and co), gasification and pyrolysis (Hušek et al., 2022; Oladejo et al., 2019).

Anaerobic digestion has already been briefly discussed for the reuse of sewage sludge in agriculture. For sludge to energy, anaerobic digestion allows the recovery of energy through the production of biogas, which contains methane, carbon dioxide, nitrogen, hydrogen, hydrogen sulphide and water vapour (Gherghel et al., 2019). Anaerobic digestion is the most applied process for biogas generation in wastewater treatment plants, and pre-treatment methods can be used to increase the amount of biogas (Gherghel et al., 2019). Anaerobic digestion is widely used despite the long reaction time and low conversion efficiency, also because of its low cost, low carbon emission and the ability to utilise organic waste with high moisture content without reducing the calorific value of the biogas produced (Oladejo et al., 2019). The biogas produced can then be used to produce biomethane or converted to heat or electricity, while the by-product can be used as fertiliser (Oladejo et al., 2019). Current research is also focusing on the production of biohydrogen from anaerobic digestion, but several challenges remain (Khawer et al., 2022)

Thermochemical processes treat the organic matter, including organic contaminants, to produce thermal energy efficiently with low reaction times and high energy recovery (Nkuna et al., 2024), but they result in the production of process products, carbon dioxide, and gaseous and solid emissions (Hušek et al., 2022). In addition, thermochemical processes require a sludge with a lower moisture content compared to anaerobic digestion (Oladejo et al., 2019), so energy must be used to dry the sludge (Taron et al., 2023). Incineration is considered an effective method of sludge treatment, as it allows the conversion of sludge into thermal energy (Zhang et al., 2023), while also reducing the volume of the sludge (Samolada and Zabaniotou, 2014). The ash produced by incineration should be disposed of or recovered: if the ash is disposed of in landfills, this may cause secondary pollution due to the release of heavy metals; alternatively, it can be used, for example, in various industries such as the production of cement and concrete, road construction, glass, ceramics (Zaharioiu et al., 2021), or further treated to recover phosphorous for use in agriculture (Hušek et al., 2022). The investment costs for the construction of incineration plants are high and can only be justified for plants that are expected to handle high volumes (Kacprzak et al., 2017). In addition, the solution faces some resistance in terms of public acceptance, as the emissions of incineration are perceived as dangerous (Samolada and Zabaniotou, 2014). Co-incineration is preferred to mono-incineration when the sludge has a low calorific value or when the total volume is low, as it couples the sludge with other energy sources such as natural gas or fuel (Cieślik et al., 2015). Symbiosis with existing facilities avoids capital investment in new incinerators and increases the utilisation rates of such facilities (Cieślik et al., 2015). Incinerators can also be easily integrated with pollutant capture technologies (Oladejo et al., 2019).

Pyrolysis is a treatment that takes place in an inert atmosphere, producing liquid pyrolytic oil, solid biochar, and non-condensable gases (Oladejo et al., 2019; Taron et al., 2023), all of which can be used as fuel to generate electricity and heat through combustion (Taron et al., 2023). Due to the operating temperatures, the process is less polluting than incineration but still requires considerable energy (Conesa et al., 2009), also because sludge with high moisture content is not suitable (Oladejo et al., 2019). The technology for pyrolysis has high investment and operating costs, with economic viability depending on various factors (Oladejo et al., 2019). Interestingly, the biochar produced contains high amounts of phosphorus and nitrates, so it can also be used as a soil amendment. In contrast to the direct application of sludge to the soil, there is a controlled release of nutrients (Bora et al., 2020; Taron et al., 2023).

Gasification involves the conversion of organic compounds into syngas (Oladejo et al., 2019; Taron et al., 2023). Gasification can be carried out using air, carbon dioxide, oxygen, steam, or a mixture of these (Oladejo et al., 2019). Syngas can be further processed into electricity or fuel, biochar can be used as biofuel, and tar can be used for building materials (Nkuna et al., 2024). Gasification is a highly energy-efficient technology, with overall limited, but still present, emissions. The technology for gasification has high investment and operational costs (Oladejo et al., 2019). A complete overview of methods and technologies for thermochemical processes can be found in (Oladejo et al., 2019; Siddiqui et al., 2023; Nkuna et al., 2024). Other sludge to energy processes are based on bio-electrochemical processes that convert the organic matter into hydrogen, methane or other valuable chemical products. These solutions are still under development and face various technical challenges (Oladejo et al., 2019). Hydrothermal technologies are also available, but their evaluation and application for sewage sludge treatment is limited, also due to limited technological maturity (Bora et al., 2020).

The recovery of *nutrients and materials* from sludge is receiving increasing attention (Wang et al., 2020b). Several materials can be recovered from sewage sludge (Siddiqui et al., 2023). The content of heavy metals, such as silver, gold, copper, iron, gallium, and chromium in sewage sludge is promising, but high economic barriers currently prevent their widespread recovery. However, given the risks posed by heavy metals in sludge to the agriculture option, their recovery could be an efficient way to address this environmental problem (Siddiqui et al., 2023). Material recovery can also include the reuse of ash from incineration in construction materials as they have a similar composition (Xia et al., 2023; Zhang et al., 2023). Ashes can be used to produce cement clinker as an alternative to raw material or conventional fuel, as well as to produce low-carbon cement or functional concrete (Xia et al., 2023). In addition, ash can also be used to produce bricks and ceramics or as a replacement for sand in certain processes (Xia et al., 2023). The reuse of sewage sludge as a building material showed good insulation performance (Hao et al., 2022), but the long-term leaching risks of toxic elements from sewage sludge-derived building materials are not thoroughly analysed and discussed (Xia et al., 2023). For a review of material recovery technologies, see (Siddiqui et al., 2023). Nutrients can also be recovered, such as nitrates, phosphorus, potassium, magnesium and sulphur (Siddiqui et al., 2023), and this route is of interest as most regions of the world are expected to suffer from fertilizers shortages (Kathi et al., 2023). Sewage sludge could also be a source of proteins that can be reused for multiple applications such as animal feed (Kathi et al., 2023) For a complete review of nutrient recovery technologies, see Gherghel et al. (2019) and Kathi et al. (2023).

2.1.2. Overperformance

Overperformance entails voluntary actions implemented by the WWU to curb noxious or undesirable effects beyond compulsory targets, or in the absence of explicit legal prescriptions. Overperformance may happen in various forms, such as blocking, monitoring, or mitigating actions (Delmas and Blass, 2010; Lyon and Maxwell, 2008). Overperformance may be a form of self or private regulation (Malhotra et al., 2019) which is usually undertaken to anticipate regulation, in case of blurry legislation, or to avoid more stringent regulation in the future (Malhotra et al., 2019); overperformance can also help dealing with CSSs, limiting their possible future retaliatory behaviour and mitigating their demands for more sustainable industrial patterns (Cagno et al., 2018). Sectors such as energy efficiency (Cornelis, 2019) and mitigation of water pollution (Evans et al., 2019) have a long tradition of voluntary schemes and negotiation of rewards with regulators. However, the voluntary adoption of advanced practices in sewage sludge management has not yet been studied by current research.

2.1.3. Vertical integration

The WWU's scope of operations may vary vertically. Specifically, several stages can be included, from the upstream water to the sewerage treatment and sludge disposal (Saal et al., 2013). Generally, vertical integration allows firms to exploit economies of scale and economies of scope, favouring diversification (Chavas and Falco, 2017; Teece, 1980) and may lead to increased coordination and control in the overall management of wastewater flows (Harrigan, 1984; Pahl-Wostl et al., 2012). Studies have evaluated the presence of vertical integration between different stages in wastewater utilities, but research is still limited, and empirical results deeply depend on the specific WWU, and context investigated (Abrate et al., 2017; Saal et al., 2013).

2.2. Regulatory framework

The European Directive that most directly addresses sewage sludge recovery is the Sewage Sludge Directive (86/278/EEC), which aims to promote and regulate the use of sewage sludge for agricultural purposes by setting the concentration thresholds for heavy metals, and the operational conditions that allow its usage. However, Member States have set widely varying thresholds for pollutants in their implementation of the Directive (Inglezakis et al., 2014). Other Directives, such as the Water Framework Directive (2000/60/EC), the Landfill Directive (1999/31/EC) and the Waste Framework Directive (2008/98/EC), complete the regulatory framework by clarifying terms and definitions and general rules for water resource management and waste management and recovery. The Waste Framework Directive also presents the waste hierarchy, which ranks the main circular economy strategies – prevention, re-use, recycling, recovery, disposal – in terms of environmental sustainability.

In general, EU legislation is mainly concerned with the agricultural use of sewage sludge, and provides incentives for other valorisation routes by setting stricter targets for the use of renewable energy sources (Renewable Energy Directive, 2009/28/EC) and restricting landfilling (Fertiliser Regulation, 2003/2003/EC, 2009/1009/EC). Table 1 reports an overview of the main regulations at EU level.

The Directives described above are then operationalised through different policy instruments in the different Member States. In general, the literature distinguishes four relevant types of policy instruments or characteristics of the regulatory environment that policymakers can use to induce private firms – in this case WWUs – to pursue environmental objectives, that is the reduction of negative externalities associated with sludge management: obligations (command and control instruments), economic instruments (i.e. environmental taxes or subsidies), information instruments, or a more stable regulatory environment.

2.2.1. Command and control instruments

Command and control instruments (CCIs) are the most traditional form of environmental policy, directly regulating the behaviour of firms or consumers through monitoring and sanctioning mechanisms (Rittberger and Richardson, 2003). They emphasise the role of direct regulation through standards and targets (Rittberger and Richardson, 2003), and include, for example, mandates to meet certain standards as well as bans or restrictions on particularly harmful technologies (e.g. landfilling). CCIs are based on the assumption that the policymaker is fully informed and willing to implement the best scenario from a social welfare perspective (Bernstein, 1993). CCIs are adopted to ensure that the possible sludge management strategies do not harm human health or the environment (Hanjra et al., 2015). Although CCIs are relatively easy to apply in pursuit of the social optimum, they may not promote innovation beyond the mandatory targets (Garrone et al., 2018b). In

Table 1
Overview of the main EU regulations related to sewage sludge management.

Directive	Reference	Main contributions to sewage sludge management
Sewage Sludge Directive	86/278/EEC	The use of sewage sludge in agriculture is encouraged. Sludge must be treated before use, but Member States may authorise the use of untreated sludge if it is injected or incorporated into the soil. The Directive sets limit values for heavy metals in soil and important operational conditions for its use.
Urban Wastewater Treatment Directive	91/271/EEC	The Directive requires collection and primary, secondary and more stringent treatment for agglomerations depending on their size. Sludge from wastewater treatments must be reused where appropriate.
Landfill Directive	1999/31/EC	The Directive bans the landfilling of liquid and untreated waste and sets restrictions and targets for biodegradable and solid waste (including sewage sludge) that is landfilled. The amendment 2018/850 imposes further restrictions on the landfilling of biodegradable waste.
Waste Framework Directive	2008/98/EC	The Directive defines the concept of the waste hierarchy: prevention, reuse, recycling and energy recovery. It allows the transport of waste for incineration between European countries.
Renewable Energy Directive	2009/28/EC	The Directive sets targets for the amount of energy to be produced from renewable sources, including biogas and sewage sludge.
Fertilisers Regulation	2003/2003/EC; 2009/1009/EC	The Directive regulates the characteristics of the market for organic carbon products used as fertilisers or soil improvers.

addition, CCIs are considered old-style regulatory policies and may be inefficient because they impose uniform abatement targets and technologies, while ignoring specific firm- and context-level factors (Rittberger and Richardson, 2003). CCIs are a widely used instruments in the regulatory framework related to sewage sludge management in the EU. Examples include the pollutant concentration targets in the Sewage Sludge Directive (86/278/EEC) and the renewable energy production targets in the Fertiliser Regulation (2003/2003/EC and 2009/1009/EC).

2.2.2. *Economic instruments*

Although strong targets and mandates are crucial for promoting sustainable practices by utilities (Garrone et al., 2017), CCIs may not be sufficient (Buysse and Verbeke, 2003; Kassinis and Vafeas, 2006). Economic instruments (EIs) include different types of environmental taxes and charges, subsidies, and tax incentive mechanisms (Rittberger and Richardson, 2003). EIs influence the relative costs or benefits of different available options, leading decision-makers to choose the most environmentally friendly options through increased revenues or reduced costs (Garrone et al., 2018b). Taxes and subsidies that influence the composition of the water tariff appear to be particularly relevant for WWUs (Cagno et al., 2022), as the water tariff, according to the so-called cost-recovery principle, transfers to consumers the costs borne by WWUs for managing sludge treatment. Other interesting EIs relate to the creation of liability funds for landowners for the reuse of sludge in agriculture, and the creation of a market for by-products obtained from a specific valorisation route (Hukari et al., 2016).

A further example are landfill taxes. Although landfill taxes were not developed to specifically incentivise sludge treatment, they are EIs that makes alternative options to landfilling more economically attractive. Indeed, since landfilling may be less expensive than alternative valorisation options that require additional and more advanced operational processes (Ye et al., 2022), landfill taxes are a way through which policy regulations aim at reducing such cost differential. Landfill taxes are implemented in different EU countries with an average value of €50/tonne, but their value varies widely as they are mostly set by national or regional governments (European Environmental Agency, 2023).

2.2.3. *Information instruments*

Information instruments (IIs) provide the public with environmentally relevant information, such as the risks, benefits and environmental and human health impacts of a given management strategy (Bichai et al., 2018; Harris-Lovett et al., 2015; McClaran et al., 2020), in order to integrate environmental awareness and responsibility into the decision-making process (Rittberger and Richardson, 2003). For example, the Sewage Sludge Directive requires sludge producers to provide users with information on the composition of the sludge every six months. IIs can reach a broad audience through information campaigns or a selected audience through tailored educational programmes (Bouwma et al., 2015). IIs can be targeted at WWUs through initiatives that aim to transfer knowledge and know-how between water service providers, thereby promoting the adoption of advanced wastewater treatment technologies (Ford et al., 2014; Garrone et al., 2018a), and untapped opportunities may emerge that are both economically and environmentally beneficial (Liao, 2018). Certification programmes and award recognition are IIs that leverage reputation (Garrone et al., 2017), while encouraging investment in sustainable options and promoting environmental innovation (Liao, 2018), and potentially opening up revenue by influencing the marketing of sludge-based products that ensure the safety of recycled goods (Hukari et al., 2016).

2.2.4. *Regulatory uncertainty*

Regulatory uncertainty is the inability to predict the future state of the regulation (Hoffmann et al., 2008). The discretion of governments, i.e. their ability to change the rules over time, may limit WWUs' willingness to sustain large-scale investments (Levy and Spiller, 1994), while a change in regulations after a sunk investment has been made discourages WWUs from making infrastructure investments in the future. Thus, the perception of regulatory uncertainty by WWUs is a (negative) policy influence that may prevent the adoption of specific sludge management strategies, as investments in these strategies could only be made with an underlying stable and clear regulatory framework. Drawing on the taxonomy proposed by Hoffmann et al. (2008), three types of regulatory uncertainty fit into sewage sludge environmental policy: (i) uncertainty about the basic direction - what state objectives are pursued and how; (ii) the measures and rules - the design and definition of regulations; (iii) the implementation process - the authority involved and the timing of implementation. Policymakers may decide to make regulations more stable and predictable to support the WWUs' investments.

2.3. *Stakeholders' network*

CSSs embody a set of shared norms, beliefs, and values that go beyond formal regulation and call on organisations to adhere to them (Mombeuil et al., 2023; North, 1990). Local CSSs have the greatest influence on the decision-making process of WWUs, and are most affected by their activities (Lienert et al., 2013). CSSs can exert pressure on the WWU, pushing it to pursue environmental performance even beyond regulated targets or towards unregulated goals (overperformance), thus changing the WWU's priorities (Cagno et al., 2018). Indeed, CSSs influence water infrastructure decisions (Lienert et al., 2013), and a WWU wants to gain legitimacy to justify its right to operate (Maurer, 1971).

2.3.1. Citizens

Citizens include residents and tourists, as well as the community surrounding the WWU in general. Citizens' priorities might differ according to their specific interests. For example, communities that derive income from recreational, or tourism activities might be more inclined to implement sustainability interventions (Garrone et al., 2018a; Keiser and Shapiro, 2019a); however, the general willingness of citizens for high environmental quality might determine a demand-pull dynamic for sustainable management (Keiser and Shapiro, 2019b; Veugelers, 2012).

Citizens might also exert pressures that induce the WWU to invest beyond the regulated targets by threatening the right of utilities to operate or blocking the adoption of unsustainable valorisation routes (Kassinis and Vafeas, 2006; Kawai et al., 2018; Khanna and Damon, 1999; Maurer, 1971). Even if citizens recognise the importance of sludge treatment to avoid pollution, environmental damage, and public health risks, they may perceive the treatment process as having negative impacts, leading to "not in my backyard" reactions (Capodaglio et al., 2016).

Blocking actions against agricultural sludge, incineration and anaerobic digestion are widely diffused (UN HABITAT, 2008). Regarding the reuse in agriculture, concerns may relate to the transfer of toxic compounds from sludge to crops, which may ultimately affect human health (Wang et al., 2008). In these contexts, nutrient recovery or other alternative valorisation routes become attractive (Ott and Rechberger, 2012). Sludge to energy options are opposed mainly because of the toxic ash from incinerators (Lindsay et al., 2000; Samolada and Zabaniotou, 2014), although citizens often confuse sludge to energy with waste to energy facilities (Samolada and Zabaniotou, 2014). For anaerobic digestion, the construction of the necessary facilities may not be accepted by citizens, who may also form local environmental committees (Capodaglio et al., 2016).

WWUs can manage opposition and reputational risks through overperformance, such as installing artificial noses to detect odours and deodorisation systems, blocking or reducing polluting activities, reducing noise from operations, reducing the amount of waste produced, and installing resistant tanks and absorbent materials to reduce the likelihood of spills on soil (Cagno et al., 2018).

2.3.2. Municipality

Municipalities may be the main or sole shareholder of the WWU (Lienert et al., 2013). Although municipalities may own and control the utilities, they are separate entities from the authorities responsible for regulating them. While they may be perceived by other CSSs as responsible for designing policies on sludge treatment (Lienert et al., 2013), municipalities primarily represent CSSs, such as voting citizens. Therefore, municipalities are considered to pose an informal rather than formal institutional pressure for the purpose of our study. Due to their property rights, municipalities are primary stakeholders, but their political linkages and role of representation of civil society also qualify them as secondary stakeholders. It is only in the latter role that they are considered here. The dynamic described above can lead to government opportunism (Goldberg, 1976; Spiller, 1993; Spiller and Savedoff, 1999). This issue is closely related to the need for municipalities to achieve political consensus, which is a strong challenge in contexts with a weak institutional background (Garrone et al., 2018a), as it might jeopardise the opportunities for WWUs to implement new projects or certain management strategies, or eliminate the possibility of increasing tariffs to repay utility investments.

2.3.3. Farmers and landowners

The use of sewage sludge in agriculture raises concerns about the potential impact of contaminants on health, safety, and the environment (Gawlik and Bidoglio, 2006; Wang et al., 2008). Farmers and landowners, who are not obliged to accept sludge on their fields, may not favour this option as their customers may react negatively to food grown with sludge (Christodoulou and Stamatelatou, 2016; Pivato et al., 2022). In addition, negative impacts of sludge use in agriculture are perceived in terms of potential exposure to pathogen transmission for workers applying sludge to land. This perception is even stronger in contexts with poor hygienic practices and lack of adequate protective equipment, exacerbating mistrust towards this valorisation route (Major et al., 2020; Mininni et al., 2015; Sabbahi et al., 2022). Certification programmes that guarantee high quality standards and local demonstration projects that show the benefits of sludge application to land are fundamental to increase the likelihood of sludge reuse in agriculture (Diaz et al., 2015; European Commission, 2001).

2.3.4. Non-governmental organisations and environmental activists

Non-governmental organisations and environmental activists (hereafter referred to as NGOs) have a dual role in influencing the WWU's decisions on sludge management (Sabia et al., 2021): while environmental and health concerns about recovery options may lead NGOs to oppose them, reducing their likelihood of adoption, environmental associations may positively influence the likelihood of adoption of more environmentally friendly options (Sabia et al., 2021; Zilinskaite et al., 2022).

2.3.5. Media

As information is central to increasing public understanding of sludge management strategies and reducing opposition, misinformation can have a negative impact on the likelihood of adoption of particular routes. The media is fundamental for informing WWUs and their stakeholders, especially citizens, about the impacts and consequences of different management options (Lienert et al., 2013). However, WWUs may be reluctant to disclose information for strategic reasons or because the information may be too complex for stakeholders (Garrone et al., 2018b). The role of information disseminated through the media and the development of sound communication systems thus becomes a fundamental aspect.

2.3.6. Water associations

Water associations are organisations and knowledge hubs for the water sector, bringing together water experts, professionals, and utilities to find solutions to water challenges. Water associations are a fundamental resource for knowledge transfer, enabling the development of participatory research networks to share best practices and create synergies (Ford et al., 2014; Garrone et al., 2018a).

2.4. Conceptual framework

The conceptual framework developed is shown in Fig. 1. In the centre of the framework, the sludge management strategies for WWUs in the field of sewage sludge management are presented, namely the valorisation route, overperformance and vertical integration. The stakeholders' network with its CSSs and the policy framework with its policy instruments are shown. The elements of the network are connected by arrows whenever a relationship between a decision (the sludge management strategy) and a contextual element (the policy instrument or the CSSs) is found in the literature. The relationships, representing the pressure, are briefly described in Table 2, while the detailed description is offered in Appendix A.

3. Methods

We conducted a multiple explanatory case study (Yin, 2009) to provide an in-depth understanding of the mechanisms that lead CSSs (stakeholder network) and policymakers (the regulatory framework) to influence the WWU's decisions in the field of sludge management strategies, particularly in terms of valorisation route choice, overperformance and vertical integration.

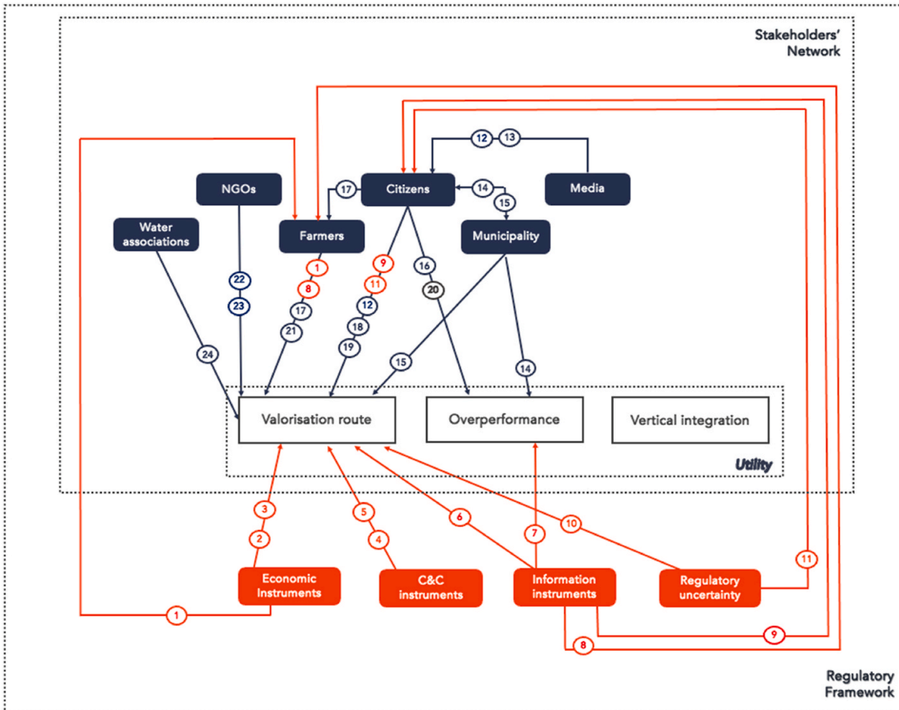

Fig. 1. The conceptual framework linking sewage sludge management strategies, stakeholders' network and regulatory framework. The description of the identified pressures in reported in Table 2.

3.1. Sample selection

Our unit of analysis is the individual WWU responsible for the sewage sludge management. We conducted case studies with a theoretical replication aim to highlight different patterns of behaviour, by selecting WWUs with different characteristics (Eisenhardt and Graebner, 2007). Although we focused on WWUs operating in urban contexts to have a close relationship with CSSs, we selected WWUs with a different basin of equivalent inhabitant served, different geographical contexts, and therefore different regulations (Lienert et al., 2013), and different organizational structures (in terms of belonging to a multi-utility or not). The sample was selected to identify possible European WWUs through direct contact (WWU1, WWU4 and WWU5), second-level contact (WWU2 and WW3) and through water associations (WWU6). The WWUs are located in Northern Italy (WWU1, WWU2, WWU3), Southern Italy (WWU6), Germany (WWU4) and Finland (WWU5). Taken together, the selected WWUs serve more than 11 million people equivalent through more than 540 wastewater treatment plants. The number of selected cases is coherent with the explanatory purpose of the study and with the suggestion of Meredith (1998) and Voss et al. (2002).

3.2. Data collection and analysis

Once the WWUs agreed to participate in the study, we collected secondary data from WWUs' reports and news. This process allowed us to gather information on economic data, the number of people served, and the processes and technological approaches used to treat wastewater. At the same time, we also collected secondary data on the legal context in which each WWU is operating. This allowed us to proceed to the second stage of the data collection with a good knowledge of the background and context of the WWUs. The next stage was the investigation within the WWUs, during which we collected primary data. We conducted the semi-structured interviews with the support of a questionnaire that allowed the addition of supplementary questions and the collection of free comments that emerged during the interview (Adams, 2015; Dicicco-Bloom and Crabtree, 2006). During the interviews, field notes were also taken by the interviewers involved in the research and a tour of the wastewater treatment plant was undertaken - where possible, due to the COVID-19 emergency. The interviews lasted on average 2.5 hours and were structured around a series of questions touching on several aspects of WWU's activities, particularly i) describing the context of the WWU's operation and verifying the secondary information; ii) identifying the most important CSSs and their pressures; iii) identifying the most important policy instruments and their pressures. The questionnaire was sent to the interviewees in advance to give them an insight into the topics to be covered during the interview. This also allowed the WWUs to select the best respondent(s) within their organisation. Each interview was conducted by a team of 3 or 4 researchers. The interviews were recorded, transcribed, coded, and triangulated with other primary and secondary data. In the event of disagreements, a second interview (either face-to-face or by telephone) was arranged for further clarification. Interviews were transcribed as soon as possible after the survey to maximise recall, facilitate follow-up and fill in data gaps (Voss et al., 2002). Further details of the data collection and the various sources of evidence are given in Appendix B; an overview of the sample and information on the interviews conducted are given in Table 3 and Table 4.

3.3. Data analysis

The interviews were transcribed (verbatim). They were then manually coded along with field notes and secondary documents collected. An abductive approach was used to analyse the evidence collected. The abductive approach to theory development requires a continuous interaction between the data from the empirical evidence and the literature (Eisenhardt and Graebner, 2007). For first-order coding, open coding was used, with themes emerging inductively from the data, allowing the identification of key aspects in the overall content; for second-order coding, axial coding was used to combine related codes and identify relevant categories. The inductive coding was then compared with a coding system developed based on the literature (Silva et al., 2018). For this step, we used the information presented in

Table 2
Description of the relationships (i.e., the pressures) considered in the study. The Table reports the relationships emerged from the review of the literature (theoretical ones) described in Section 2 and anticipates the relationships supported from the empirical investigation conducted through the case studies, whcih will be described in Sction 4. Legend: ✓ Supported; ✗ Not emerged/Not supported.

		Pressure type			Emerged from the literature	Supported by case studies
Policy instruments	Economic instruments	1	A	Liability funds for farmers	(Garrone et al., 2017; Rittberger and Richardson, 2003)	✗
		2	A	Incentives	(Garrone et al., 2017; Keiser and Shapiro, 2019a; Rittberger and Richardson, 2003)	✓
			B	Lack of incentives on other routes	Rittberger and Richardson (2003)	✗
			C	Taxes or fines on other routes	(Garrone et al., 2017; Rittberger and Richardson, 2003)	✓
			D	By-products marketing allowed	(Hukari et al., 2016; Keiser and Shapiro, 2019a; Rittberger and Richardson, 2003)	✓
		3	A	Lack of incentives	Rittberger and Richardson (2003)	✓
			B	Incentives on other routes	(Garrone et al., 2017; Keiser and Shapiro, 2019a; Rittberger and Richardson, 2003)	✗
			C	Taxes or fines	(Garrone et al., 2017; Keiser and Shapiro, 2019a; Rittberger and Richardson, 2003)	✓
	Command & Control instruments	4	A	Loose standards	(Buysse and Verbeke, 2003; Kassinis and Vafeas, 2006)	✓
			B	Stringent targets	(European Commission, 2010; Garrone et al., 2017; Hanjra et al., 2015; Rittberger and Richardson, 2003)	✓
			C	Strict standards on other routes	(European Commission, 2010; Rittberger and Richardson, 2003)	✓
			D	Loose targets	(Buysse and Verbeke, 2003; Kassinis and Vafeas, 2006)	✓
			E	Sludge export because of stringent standards	✗	✓
		5	A	Stringent standards	(European Commission, 2010; Garrone et al., 2017; Hanjra et al., 2015; Rittberger and Richardson, 2003)	✓
			B	Loose targets	(Buysse and Verbeke, 2003; Kassinis and Vafeas, 2006)	✓
			C	Loose standards on other routes	(Buysse and Verbeke, 2003; European Commission, 2010; Hanjra et al., 2015; Kassinis and Vafeas, 2006)	✗
			D	Stringent targets on other routes	(European Commission, 2010; Garrone et al., 2017; Hanjra et al., 2015; Rittberger and Richardson, 2003)	✗
	Information instruments	6	A	Information campaign toward utilities	(Bouwma et al., 2015; European Commission, 2010; Garrone et al., 2017; Hukari et al., 2016; Liao, 2018; Rittberger and Richardson, 2003; Synnestvedt, 2001; Tietenberg and Wheeler, 2001)	✗
			B	Certification programs and benchmarking regulation	(Bouwma et al., 2015; Garrone et al., 2017; Liao, 2018; Rittberger and Richardson, 2003; Synnestvedt, 2001; Tietenberg and Wheeler, 2001)	✗
			C	Certification of by-products	(Bouwma et al., 2015; Garrone et al., 2017; Hukari et al., 2016; Liao, 2018; Rittberger and Richardson, 2003; Synnestvedt, 2001; Tietenberg and Wheeler, 2001)	✗
		7	A	Utility's certification	(Bouwma et al., 2015; Garrone et al., 2017; Hukari et al., 2016; Rittberger and Richardson, 2003; Synnestvedt, 2001; Tietenberg and Wheeler, 2001)	✗
		8	A	Local demonstration projects	(Bouwma et al., 2015; European Commission, 2010; Liao, 2018; Rittberger and Richardson, 2003; Synnestvedt, 2001; Tietenberg and Wheeler, 2001)	✗
		9	A	Information campaigns toward CSSs	(Bouwma et al., 2015; European Commission, 2010; Liao, 2018; Rittberger and Richardson, 2003; Synnestvedt, 2001; Tietenberg and Wheeler, 2001)	✗
	Regulatory uncertainty	10	A	Regulator's discretion	(Hoffmann et al., 2008; Levy and Spiller, 1994)	✓
			B	Ambiguity in regulations	(Hoffmann et al., 2008; Levy and Spiller, 1994)	✓
			C	Red tape in investments approval	(Garrone et al., 2018a; Levy and Spiller, 1994)	✓
			D	Municipalities' assembly	✗	✓

(continued on next page)

Table 2 (*continued*)

		Pressure type			Emerged from the literature	Supported by case studies
			E	Emergency due to sudden regulation changes	✗	✓
		11	A	Lack of information in citizenship	(Hoffmann et al., 2008)	✓
		25	A	Voluntary adequation to EU leading countries	✗	✓
			B	Diversification of routes caused by regulator's discretion and ambiguity	✗	✓
			C	Regulator's discretion in sludge disposal pricing	✗	✓
		26	A	Information sharing	✗	✓
			B	Voluntary action to balance regulatory uncertainty	✗	✓
		27	A	Regulator's discretion in pricing	✗	✓
Civil Society Stakeholder	Media	12	A	Raise awareness of citizenship	(Bouwma et al., 2015; Liao, 2018; Lienert et al., 2013)	✗
			B	Provision of accurate information to citizenship	(Liao, 2018)	✗
		13	A	Provision of inaccurate information to citizenship due to misinterpretation of technical information	(Garrone et al., 2018b)	✓
	Municipality	14	A	Pollution control systems	Cagno et al. (2018)	✓
			B	Mitigation actions	Cagno et al. (2018)	✓
		15	A	Governmental opportunism - block of recovery options	(Garrone et al., 2018a; Goldberg, 1976; Spiller, 1993; Spiller and Savedoff, 1999)	✓
			B	Governmental opportunism - highlight of positive externalities	✗	✓
	Citizens	16	A	Similar to 14 A	(Cagno et al., 2018)	✗
			B	Similar to 14 B	(Cagno et al., 2018)	✓
		17	A	No market for food produced using sludge as a soil improver	(European Commission, 2001)	✓
		18	A	Resistance to pollution abatement technologies	(Garrone et al., 2018a)	✗
			B	Availability of nearby clean water	(Keiser and Shapiro, 2019b)	✗
			C	Not In My Back Yard	(Capodaglio et al., 2016)	✓
			D	Environmental concerns (sludge leaching into the soil)	(Gawlik and Bidoglio, 2006; Lindsay et al., 2000; Wang et al., 2008)	✓
			E	Environmental concerns (ash)	(Samolada and Zabaniotou, 2014)	✓
			F	Concerns about construction of new facilities	(Capodaglio et al., 2016)	✗
		19	A	Communities based on tourist activities	(Garrone et al., 2018a)	✗
			B	Environmental awareness	Keiser and Shapiro (2019b)	✓
			C	Stakeholders' disinterest	✗	✓
		20	A	Build dialogue and trust	(Garrone et al., 2018a, 2017; Khanna and Damon, 1999; Maurer, 1971; Wehn and Montalvo, 2018)	✓
	Farmers	21	A	Health concerns	Mininni et al. (2015)	✓
	NGOs	22	A	Promotion of sustainable practices	(Gray and Wiedemann, 1999)	✓

(*continued on next page*)

Table 2 (*continued*)

	Pressure type			Emerged from the literature	Supported by case studies
	23	A	Environmental and health concerns	(Sabia et al., 2021)	✓
Water associations	24	A	Transfer of knowledge and know-how	(Ford et al., 2014; Garrone et al., 2018a)	✓
	28	A	Advocacy	✗	✓
Local industries	29	A	Industrial symbiosis	✗	✓

Table 3

Overview of the sample. Legend. WWU: Wastewater Utility; MSPE: Millions of served people equivalent; WTPs: Water Treatment Plants.

WWU	Region	MSPE	WTPs	Valorisation Route adopted
WWU1	Northern Italy	2.2	40	Spread in field (45%); Co-incineration (39%); Cement plants (4%); Gypsum of defecation (4%); Landfill (4%)
WWU2	Northern Italy	0.6	54	Co-incineration (80%); Agriculture (20%)
WWU3	Northern Italy	2.2	413	Gypsum and compost (70,1%); Cement plants (29,7%); Landfill (0,2%)
WWU4	Germany	4	6	Mono-incineration (56%); Co-incineration (44%)
WWU5	Finland	1.3	2	Compost (100%)
WWU6	Southern Italy	0.8	31	Landfill (90%); Compost (10%)

Appendix A. The coding was performed independently by three different researchers, and the final coding structure was revised and approved by all authors. This procedure also eliminated possible biases. The emerging evidence and the provided reconciliation with the existing literature allowed for the validation of the conceptual framework presented in Fig. 1. The overview of the data structure is provided in Appendix C. We assessed the methodological rigour considering the four design tests proposed by Yin (2009), using the tactics suggested by the literature (Baškarada, 2014; Eisenhardt, 1989; Voss et al., 2002; Yin, 2009). Reliability was assessed by conducting multiple case studies, defining a case study protocol, and the presence of multiple interviewers. For construct validity, we created an electronic folder containing all the data for each case, to ensure a chain of evidence, and triangulated information deriving from multiple sources of evidence, which also ensured internal and external validity. To increase the external validity, and thus the generalisability of our findings, we used different strategies: we selected cases representing a variety of settings, thus broadening the potential for generalisation (Yin, 2009); we conducted a cross-case comparison, comparing and contrasting cases to identify similarities, differences and patterns (Eisenhardt and Graebner, 2007); we explained our data collection methods and analytical procedures (see Appendix C) (Yin, 2009); we discussed the limitations of our findings (see section 4.2.2) (Flyvbjerg, 2006).

4. Results and discussion

The section reports (section 4.1) and discusses the findings assessing them against the current literature (section 4.2). Our research questions focused on understanding the role of policy instruments and CSSs in influencing sludge management strategies. From this point, the presentation of the results is organised according to the identified management options, understanding for each of them the influence of policy instruments and CSSs, the most relevant policy instruments and CSSs, and possible interactions between them. Details of the empirically identified pressures can be found in Appendix A.

4.1. Overview of the results

The presentation of the results is organized according to sewage sludge management strategies. An overview of the results obtained in terms of relationships identified in each WWUs is reported in Table 5.

4.1.1. Valorisation route

As far as policy instruments are concerned, they seem to influence the choice of the valorisation route. EIs exert both positive (i.e. enabling) and negative (i.e. inhibiting) pressures on the choice of valorisation route. In particular, the provision of incentives (pressure 2A), as green certificates, in line with the Renewable Energy Directive 2009/28/EC, and the creation of a market for co-products (pressure 2D) increase the likelihood of adopting certain routes, such as sludge to energy with the production of biogas and sludge to agriculture with the production of

Table 4

Information on the performed interviews.

WWU	Interviewees	Duration (h)	Place	N. of interviewers	N. of transcription pages
WWU1	R&D Director Director of Planning and Control activities Director of Operations	3	Headquarter	4	27
	R&D Director Director of Planning and Control activities Director of Operations Director of wastewater treatment and sewerage	2	Headquarter	4	15
WWU2	Director of wastewater treatment and sewerage	2	Headquarter	4	18
WWU3	R&D Director Director of WTP	3	Headquarter	4	31
WWU4	Chief Engineer of WTP R&D Director Asset management manager	3	Headquarter	3	15
WWU5	Division Director Head of the composting unit	3	Skype	3	17
WWU6	Director of environmental and wastewater treatment department	3	Skype	3	21

Legend. WWU: Wastewater Utility; WTP: Water Treatment Plant.

Table 5

Overview of results of interviews. The table presents the relationships identified in each sample WWUs for each sewage sludge management strategy.

		Valorisation Route	Overperformance	Vertical Integration
Policy Instruments	*Economic Instruments*	WWU1, WWU2, WWU3, WWU4, WWU5, WWU6		
	Command and Control Instruments	WWU1, WWU2, WWU3, WWU4, WWU5, WWU6		
	Information Instruments			
	Regulatory Uncertainty	WWU1, WWU2, WWU3, WWU5	WWU1, WWU3, WWU6	WWU1, WWU2, WWU3, WWU4, WWU6
Civil Society Stakeholders	*Citizens*	WWU1, WWU2, WWU3, WWU4, WWU5, WWU6	WWU1, WWU2, WWU3, WWU4, WWU5, WWU6	
	Municipality	WWU2, WWU3, WWU5	WWU1, WWU3, WWU5	
	Farmers	WWU5, WWU6		
	NGOs			
	Media	WWU1		
	Water associations	WWU1, WWU2, WWU3, WWU5, WWU6		
	*Local Industry**	WWU1		

Legend: * Emerged from the case studies.

fertiliser:

> "Regarding incentives for biogas and electricity production, there are market certificates available." (WWU3)

> "The ultimate objective is to extract phosphorus from the ash […] and sell it. However, the success of this venture will depend not just on our ability to do it well, but also on the creation of a market for it, any incentives that may be offered for the recovery of critical materials such as phosphorus." (WWU1)

The absence of EI is effective as a barrier. This is particularly true for Italian WWUs, where the perception that no tariff increase will be granted limits investment in innovative projects (pressure 3A).

As for CCIs, the setting of standards and targets for WWUs to be compliant with (pressures 4A, 4B, 4C, 5A) are perceived as influential. They act as both barriers and enablers:

> "Incineration generates a significant amount of ash, which cannot be utilized according to our legislation." (WWU5)

> "In German law, there is a paragraph that requires the use of sludge for energy." (WWU4)

CCIs seem to have a strong influence on the route choice of WWUs. CCIs have been instrumental in limiting the sludge to landfill route (as in Italy with the ARERA's Regulation of Technical Quality – RQTI, based on Resolution 637/2023/R/idr) and reducing the viability of the sludge to agriculture route (as in Germany, with the Act Reorganising the Law on Closed Cycle Management and Waste, namely Kreislaufwirtschaftsgesetz of 2012 and the Federal Immission Control Act, namely Bundes-Immissionsschutzgesetzes in 2013):

> *"*[They have to move away from sludge to landfill route] for the ARERA penalties.*"*(WWU2)

> "We couldn't use sludge for agricultural spreading due to its high metal concentration." (WWU4)

Utilities have therefore opted for an alternative valorisation route or to export the sludge to countries where restrictions are less stringent (pressure 4E):

> "We export sludge to France, where agriculture regulations are more lenient than ours." (WWU1)

It is interesting to note that CCIs can have different effects depending on the local institutional context and specific national regulations. For example, the Italian WWU1 and WWU2 highlighted how the restrictions imposed by local regulations on the use of sewage sludge in agriculture , in terms of the presence of specific elements, prohibit the valorisation route (deriving from the Legislative Decree 109/208, also known as "Decreto genova"), whereas in Finland the CCIs instruments support more directly the valorisation of sewage sludge in agriculture (Fertiliser Product Act 539/2006, namley Lannoitevalmistelaki).

Regulatory uncertainty emerged as a strong influence on the choice of valorisation routes and WWUs try to manage uncertainty through diversification. This is the case, for example, of WWU3, which has installed thermal dryers capable of providing a dry matter suitable for different valorisation routes, to counteract the regulatory uncertainty and possible sudden changes in legislation that characterise the context in which it operates:

> "We have two thermal dryers that can exceed 90% dry matter. This was a deliberate decision made about fifteen years ago. Today, it provides flexibility as the material can also be used for cement factories through energy recovery, rather than just controversial agricultural recovery. This has allowed for a good diversification of destinations." (WWU3)

To counteract the regulatory uncertainty, WWUs, especially Italian ones, are also moving towards the adoption of paths that are currently perceived as the most accepted at European level, foreseeing a convergence of all European regulations (pressure 10A). This is the case of WWU1, for example, which has taken the route of converting sewage sludge into energy, even though this is not yet standard practice in Italy:

> "We have a European perspective which influences our decisions. We choose to incinerate waste mainly because it is a common practice in most countries around the world, with the exception of Italy." (WWU1)

Perceived regulatory uncertainty stems from sudden regulatory changes (pressure 10A), lack of clear directives (pressure 10B) or excessive bureaucracy (pressure 10C).

CSSs appear to be an obstacle to the adoption of certain valorisation route choices, and, in particular, the strong relationship between pressures from citizens and municipalities should be emphasised. For example, the implementation of incineration is particularly controversial in Italy and may suffer from opportunistic opposition from municipalities (pressures 15A and 15B), which may take advantage of public opposition (pressure 18E). These mechanisms have been observed, for example, in WWU3, where the construction and subsequent operation of an incineration plant is strongly opposed by citizens and, with a scaling effect of opportunistic behaviour, by the municipality:

> "It is highly probable that the administrators of that region will suggest finding an alternative location for the mono-incinerator […] The issue with the mono-incinerator is solely a matter of public acceptability." (WWU3)

The role of municipalities in determining the geographical location of plants was also highlighted in other European countries. In Germany, municipalities did not grant permission for a new incineration plant due to opposition from residents, while in Finland WWUs had to close an existing plant and rebuild it elsewhere:

> "25 years ago, when we planned to build another incinerator, we faced significant opposition from residents, citizen initiatives, and permit issues. The residents were concerned about the impact on their homes, including shading and proximity to the plant. As a result, we ultimately decided to shut down the entire plant." (WWU4)

> "The current plant located on the western side of the metropolitan area is situated near the sea. The city plans to repurpose the area for residential purposes, so the plant will be closed. In ten years, there will be new apartments near the seaside, and our treatment plant will be relocated inside a nearby rock formation." (WWU5)

The role of other stakeholders appears peripheral compared to citizens and municipality, but interesting patterns arose. Farmers and landowners emerged as relevant in those contexts where the selected valorisation route, i.e., composting, has in farmers an important relational counterpart, as in WWU5.

The contribution of water associations in terms of knowledge transfer (pressure 24A) is reported as an incentive for WWUs to think about innovative projects. This is the case, for example, with WWU6, which sees participation in national and international water associations as a perfect way to get involved in a specific technical discussion on sludge and to learn about innovative solutions:

> "We take part in the discussion tables […] where new technologies are presented to utilities before they are put on the market. In this way, it is possible to validate the interest in the technology as well as its feasibility, also thanks to industrial trials […] Thanks to these meetings, we got to know several innovative technologies." (WWU6)

The same applies to cooperation with local industries (pressure 29A). The pressure came from WWU1, which is currently collaborating with various industrial realities. A first collaboration is with a chemical company with a project for the reuse of resources from sludge management, such as the reuse of microplastics; a second project, focused on industrial symbiosis, involves collaboration with a food company for the recovery of specific nutrients from expired food using the WWU's technologies, which will provide the WWU with elements to be reused in the treatment of sewage sludge.

4.1.2. Overperformance

Regulatory uncertainty is the only policy instrument that influences overperformance. As WWUs' decisions are not strongly supported by the current regulation, they feel under pressure to legitimize their decisions and avoid possible consequences with the CSS (pressure 26).

Concerning CSSs, municipalities and citizens emerged again as relevant stakeholders. Municipalities seem to induce overperformance usually in the planning phase of the adoption process of new solutions (pressure 14A) or to mitigate the effects of the treatment processes (pressure 14B). An example of the latter is WWU3, where the emissions of a plant are well below the legal limits, also thanks to the cooperation between the utility and the municipality during the renovation of the treatment plant:

> "From an emissions standpoint, all necessary precautions have been taken in collaboration with the metropolitan city during the revamping of the post-combustion of the fumes […] emissions remain very low, below the regulation requirements." (WWU3)

Focusing on citizens, two main types of overperformance emerged. The first overperformance relates to the perceived odour emissions due to the sludge treatment and the related activities of deodorization beyond the regulatory constraints (Pressure 16B). Almost all the sampled WWUs underlined how often they were in a situation of overperformance to contrasting odours or noise emanating from the treatment plant, even though the emission levels were in line with the limits imposed by the regulation:

> "We are getting better and better results in terms of […] odour and noise reduction. So our regulation is just like a cover, a lid, and our internal targets are the main drivers of the operation and those are also related to our incentive system. […]. And to meet this internal target, we always have to overperform beyond what is regulated." (WWU5)

However, this is not the case in all WWUs. In Germany, for example, demonstrating that the utility is complying with the limits imposed by the regulation is a strong deterrent to the potential expansion of citizen action:

> "They complained about the noise and smell, but you can demonstrate that you are within regulations, and they will not complain further." (WWU4)

The second overperformance relates to actions carried out by WWUs to gain legitimacy from the CSSs.

> "If residents exert high pressure, it can harm our reputation and public relations." (WWU4)

These actions include, for example, information activities aimed at citizens. These activities are considered necessary from the point of view of the WWUs to compensate for the perceived lack of IIs aimed at making citizens aware of the benefits of sludge treatment (pressure 20A). Examples of said actions are the opening of the plants to visitors, or the sharing of information via social media:

> "We have a presence on Facebook, Twitter, and our website. Additionally, we organize conferences and open our plants once a year to involve citizens and showcase our sustainability efforts. We also allocate a significant amount of time to hold transversal meetings where we listen to their complaints, desires, and needs." (WWU1)

> "If they want to visit our plants, our door is open. We also organize open days for citizens. We also have a dialogue with schools, from middle schools to MBA programs." (WWU6)

Overperformance could also be achieved by providing in-kind compensation through the development of the affected areas, including the recruitment of staff from neighbouring districts, as in the case of WWU4, or even by requesting exemption from paying water and waste tariffs for people living in the vicinity of treatment plants - although this request cannot be realised for legislative reasons.

4.1.3. Vertical integration

Regulatory uncertainty emerged as the only relevant factor affecting WWUs' decisions on vertical integration (pressure 27A). This relationship has been identified mainly in the Italian context, due to the higher perceived regulatory uncertainty. Specifically, as regulation is perceived as unclear and subject to possible sudden changes, Italian WWUs try to diversify the possible valorisation routes, also by increasing vertical integration and protecting themselves from market fluctuations:

> "We have considered two options: selling it on the external market or building our own plant. Prices on the external market, whether national or international, have increased significantly due to misinformation and a decrease in supply, particularly in the agricultural sector. This is due to both unlawful behaviour and regulatory changes." (WWU1)

Sludge to energy plants are seen as a useful solution to protect against possible increases in sludge disposal costs due to changes in the regulations on the use of sludge in agriculture:

"This is a problem that affects everyone at a national level: sludge disposal. […] Some have better-equipped themselves with their own incinerators or thermal facilities, while others are in much more complex condition" (WWU2)

4.2. Discussion

The results of the empirical analysis allow us to validate and extend the conceptual framework derived from the literature review. The extended conceptual framework is presented in Fig. 2. Please refer again to Table 2 and Appendix A for a synthetic and detailed description of pressures.

4.2.1. Pressures exerted by civil society and policymakers

Regarding the role of policy instruments, it is widely accepted that EIs influence the decisions of the utility (Rittberger and Richardson, 2003). However, the role of EIs seems to be mostly related to creating barriers to investment in the absence of EIs, rather than proactively stimulating it, as the decision ultimately depends on other factors. The role of CCIs in promoting a particular route reduces the likelihood of alternatives being adopted. This is particularly the case for the sludge to agriculture/sludge to energy strategies, where CCIs create barriers to agricultural reuse and landfilling, and at the same time favour the choice of incineration. In contrast to the previous literature (Bouwma et al., 2015; European Commission, 2010; Garrone et al., 2017; Liao, 2018) IIs did not emerge as a decisive factor in guiding the choice of WWUs. A novel aspect that emerges is regulatory uncertainty as a pivotal factor in determining the WWU's management strategies. The most common dynamics we observed are related to the increasing price demanded for sludge disposal and the parallel tightening of regulation on sludge spreading on fields in several European countries.Both dynamics pave the way for other valorisation routes, mainly sludge to energy in the form of incineration, and also for vertical integration in order to be shielded from unstable prices in external markets. Regulatory uncertainty seems to be greater in contexts where the ability of politicians to commit is perceived as weaker, as in the Italian case, in line with Levy and Spiller (1994).

Regarding CSSs, it is confirmed that the municipalities, as representatives of citizens, influence the choices related to the valorisation route and the level of overperformance (Cagno et al., 2021), also due to governmental opportunism (Garrone et al., 2016). However, the role of citizens is the most relevant: their importance is perceived mainly by Italian utilities, and Italian utilities overperform to consolidate their image and reputation in the eyes of citizens to a greater extent than foreign utilities. The level of overperformance may reflect the degree of influence that citizens exert on the utility, reflecting the utility's concern that opposition from citizens may undermine its right to operate. It cannot be excluded that this concern stems from the idea that the Italian policymaker, being more prone to create problems of regulatory uncertainty, could also be more subject to the political consensus resulting from satisfying the demands of the electorate. However, although this aspect emerges as an underlying theme in the Italian case studies, it is never directly addressed. Pressure from farmers emerged, in line with European Commission (2001) and Mininni et al. (2015), but its relevance seems to have been reduced by the declining importance of the sludge to the agriculture route, which is expected to be implemented less and less in the future. No pressure from NGOs impacting the decision-making process of the WWUs emerged. Similarly, the role of the media is peripheral in the overall framework, and media's role in disseminating information to stakeholders is not relevant to our empirical analysis. Water associations have been identified as a source of knowledge useful for the implementation of innovative recovery options, as reported by Ford et al., (2014) and Garrone et al. (2018a). Furthermore, membership in water associations to lobby policymakers is an aspect not reported in previous research but emerged from the analysis of the cases. Also new compared to previous findings is the possibility for utilities to benefit from symbiosis with local industries (Neves et al., 2020). The synergies exploited may concern technical advantages for the implementation of given valorisation routes, or the possibility of relying on the partner's reputation for the

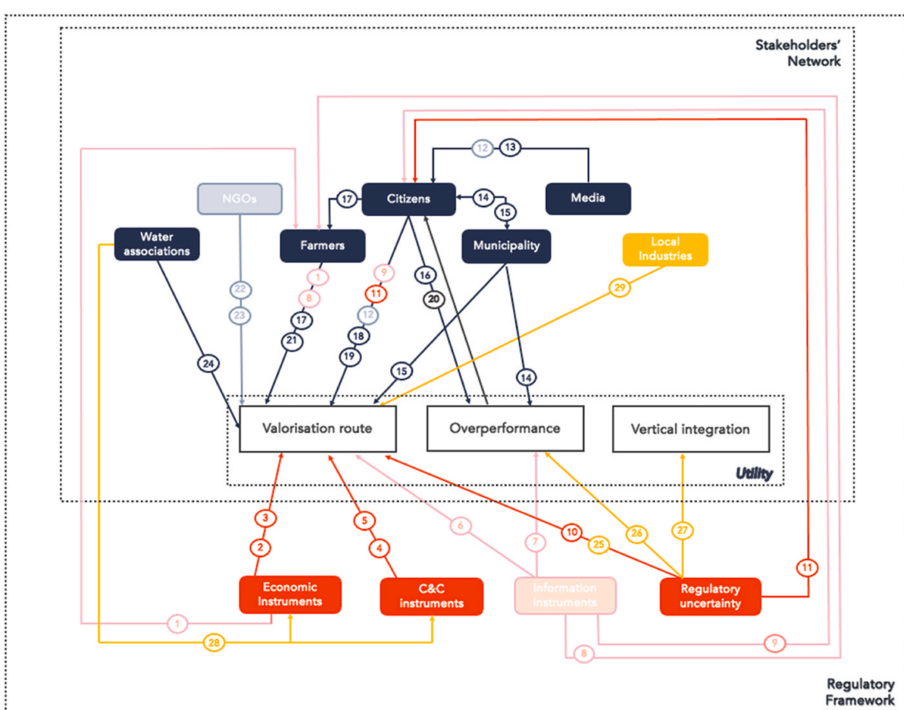

Fig. 2. Results from the validation of the conceptual framework linking sewage sludge management strategies, stakeholders' network, and regulatory framework. Legend: the yellow elements emerged from the empirical investigation and are new compared to the literature; the fading elements were not confirmed by the empirical validation; the remaining elements were found in the literature and confirmed by the empirical validation.

commercialisation of sludge-based products.

We also found that the possibility to pursue diversification and vertical integration was higher for WWUs that were part of a multi-utility group (WWU2); not being part of a multi-utility but having specific investment capacity and overall knowledge and competencies can also be extremely helpful for the vertical integration of the WWU (WWU1 and WWU6). Interactions between the role of policy instruments and CSSs can also be highlighted. In the Italian case, the lack of commitment of a regulator to raise awareness on the benefits of sustainable sludge management is seen as an obstacle to the implementation of those options that may have low public acceptance. In addition, the Finnish case reports how water associations of wastewater utilities can lobby and put pressure on policymakers to approve sludge regulation. Also, the interaction between formal and institutional pressures is shown to differ depending on the institutional context. For example, while Finnish utilities have to overperform regulations to comply with civil society demands, German CSSs seem to be satisfied when the utilities show to respect regulatory requirements. Future research should consider the characteristics of WWUs and their influences on the responses that WWUs offer to the intricate system of pressures coming from formal and informal institutions.

The above discussion highlighted the relevance of both formal and informal institutions in influencing the sludge management strategies chosen by WWUs, and supports a better understanding of the relationship between the two. Our results also contribute to another cluster of studies belonging to the institutional theory, those that emphasise the consequences of regulatory commitment versus regulatory discretion on utilities' incentives to invest (Spiller, 1993; Spiller and Savedoff, 1999). Focusing on the pressures influencing the strategies of WWUs, coercive pressures in the form of CCIs emerged as relevant, in line with David et al. (2019). As discussed above, in the presence of regulatory uncertainty, WWUs tend to imitate other WWUs. This is particularly true for Italian WWUs, which report experiencing an institutional void (Barbalet, 2023), and a lack of regulatory commitment (Spiller, 1993). To protect themselves from institutional uncertainty, they apply a mimetic form of isomorphism (David et al., 2019) taking as a reference model leading WWUs from countries other than Italy. Normally, isomorphism takes place in organisations operating in the same institutional field, that is, in a context subject to the same pressures from both formal and informal institutions (DiMaggio and Powell, 1983). Interestingly, this is not the case here, as the Italian WWUs are inspired by decisions made by WWUs in a different institutional field. However, Italian WWUs have experienced the convergence of Italian policymakers to other European policymakers that led the regulatory trends, and expect that the Italian regulation of sludge management will evolve in the same direction as other European countries, explicitly supporting the sludge to energy valorisation route.

There is a general similarity in the activities performed to legitimize own strategies with informal institutions, and they are mainly reflected in the overperformance undertaken, such as the information campaigns or the further reduction of odour and noise emissions beyond the compulsory limits. From this standpoint, the participation of WWUs in water associations might enforce a shared sense of what is appropriate in terms of the adoption of certain overperformance practices (David et al., 2019).

The debate on the relationship between formal and informal institutions is an ongoing one. From the results obtained, it can be seen that where formal institutions are stronger, in the sense that clear legislation is provided, informal institutions tend to be congruent or decoupled, i.e. they mutually reinforce the formal institutions and allow activities to vary according to practical considerations while maintaining the formal structure (Nee, 1998). This relationship is experienced, for example, by WWU4 and WWU5. Interestingly, strong formal institutions can also limit the reach of informal ones. This is the experience of WWU4, for example, where the law gives citizens a limited time to raise concerns about the treatment plants during their construction phase. In the case of weaker formal institutions, which can manifest themselves in regulatory uncertainty (Puffer et al., 2010), informal institutions may partially fill this void, so that utilities will try to maximise the legitimacy gained, for example through the overperformance activities mentioned above.

4.2.2. Contributions, limitations, and opportunities

The research provides insights into possible choices of WWUs in the context of sewage sludge management, as well as an understanding of the mechanisms that shape and influence such choices through pressures from the stakeholders' network and the policy framework. The paper thus contributes to the debate on the role of stakeholders in stimulating innovation in the water and regulated sectors, and more generally in stimulating sustainable and environmentally friendly innovation, beyond the purely technical aspects of sewage sludge treatment.

By exploring an area of research partially overlooked by the previous literature, the present research offers several contributions. The results provide a clear understanding of why WWUs might not always follow purely economic reasonings but can also be subject to a variety of institutional pressures. Policymakers gain an understanding of the impact of policy instruments on WWUs' choices, which can inform future regulations and standards. WWUs' decision-makers gain valuable insights into the factors influencing their choices and the dynamics within other WWUs. For academics, a new framework of relationships between sludge management strategies, WWUs and policy instruments is developed and offered; additionally, our results add evidence to the broad literature on mimetic isomorphism as a strategy that organisations adopt in uncertain environments. Such a framework could be used as a starting point for future research. Technology providers can finally be informed on the main pressures that the WWUs value in selecting a specific valorisation route.

The research has some limitations. The study focuses on the European policy and institutional framework, which may prove restrictive when analysing sludge management in general. Relevant differences may emerge from examining alternative socio-economic and institutional contexts in other high-income countries and middle- and low-income countries. Future research could seek to replicate our analysis in different national contexts and for other types of decisions related to sustainable innovation. For example, it might be interesting to understand the transferability of our results to slightly different settings, such as the treatment of faecal or industrial sludge, and the reuse of water for agricultural or industrial purposes (Neri et al., 2024). As for faecal sludge, for example, wastewater treatment facilities are not always available and their increasing production poses a serious problem when treated by on-site sanitation systems (Harada et al., 2016; Jain et al., 2022; Nicholas et al., 2023). We selected and investigated key sludge management strategies that emerged as relevant from the analysis of the existing literature and theoretical framework, and triangulated them with empirical evidence, but additional strategies that have not yet been captured in the existing literature may already be in place. The study is limited in terms of the temporal focus of the analysis. Indeed, in a constantly and rapidly changing world, the influence of CSSs and regulation may change as regulations are updated and the urgency of certain issues changes for different types of CSSs, as well as their beliefs and concerns. Finally, as a qualitative research design implies, by using a case study method, we prioritised depth of analysis over statistical validation of our findings. Despite the countermeasures taken to ensure reliability, construct, internal and external validity (as described in section 3.3), we only studied a sample of WWUs. It may be difficult to generalise the findings to a wider population and in different contexts. Based on our study, further research could statistically test the findings with larger surveys. The study assesses the presence/absence of specific pressures and may provide some insights into the frequency of occurrence as a proxy for relevance, but does not provide a means of numerically assessing the significance of a pressure. Such an assessment could be included in the statistical evaluation of the results mentioned above.

5. Conclusions

Our research contributes to bridging the gap between theory and practice in the field of sludge management decisions of WWUs by conceptualising and then empirically testing the role of pressures influencing sludge management strategies, with a particular focus on the role of policy instruments and CSSs. EIs and CCIs exert both positive and negative pressures on the choice of valorisation route, while regulatory uncertainty plays a significant role in shaping WWUs' sludge management strategies. Municipalities and citizens emerge as influential CSSs, particularly in determining the level of overperformance of WWUs, especially in terms of information and limitation of emissions (odours, noise) beyond regulatory limits.

Formal regulations (policy instruments) and informal institutions (CSSs) interact in shaping WWUs' strategies. Strong formal institutions may limit the reach of informal institutions, while weaker formal institutions may lead to a partial filling of the institutional void by informal institutions, leading to practices such as overperformance to gain legitimacy.

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CRediT authorship contribution statement

Alessandra Neri: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Andrea Rizzuni:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Methodology, Conceptualization. **Paola Garrone:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Enrico Cagno:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are provided in the Appendix

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Appendix A. Supplementary data

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