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Coverage and Treatment Processes of Nordic Wastewater Treatment Plants from the Perspective of EU Urban Wastewater Treatment Directive revised in 2024

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Abstract: Understanding wastewater treatment plant (WWTP) coverage and treatment processes in Nordic countries (Finland, Sweden, Norway, Denmark, Iceland, and their autonomous regions) is important in efforts improving sustainable sanitation and in implementation of upcoming new legislative requirements for urban wastewater treatment. The recast of Urban Wastewater Treatment Directive came into force in beginning of 2025 and mandates setting up national systems for wastewater surveillance, and mandates monitoring of antimicrobial resistance (AMR), in wastewater influent (pre-treatment) and effluent (post-treatment) across European Union (EU) or the European Economic Area (EEA) countries. Monitoring influent and effluent informs operational efficiency, provides wastewater surveillance (WWS) to track population health, and assesses the risks of anthropogenic pollutants and pathogens in the receiving waters. This study investigates WWTP coverage, treatment methods, and operational challenges in the Nordics via analyzing the outcomes received from a Webropol survey of environmental authorities, wastewater experts, and policymakers. Survey results were fortified with systematic review of peer-reviewed publications and government documents. We found, ~85–90% of the Nordic population is connected to centralized WWTPs, highlighting the feasibility of WWS for public health monitoring. Treatment processes vary across the region, shaped by population density, their location either in coastal or inland, or the sensitivity of recipient water bodies. Survey revealed, secondary treatment is nearly universal in Sweden and Finland but covers only about 4% of WWTPs in Iceland. Finland, Sweden, and Denmark enforce strict effluent standards, while Norway and Iceland face challenges in adopting similar practices due to harsh terrain, cold climates, and the practicality of discharging wastewater effluents into the oligotrophic Atlantic Ocean.

Keywords: Nordic countries; wastewater treatment; wastewater-based surveillance; public health; wastewater coverage

1. Introduction

Wastewater contains diverse mixture of anthropogenic contaminants, including pathogens excreted by individuals from community through feces, urine, saliva, nasal secretions, lesion materials, and other body fluids, regardless of their infection symptomatic status[1–3]. Wastewater

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treatment plants (WWTPs) play a vital role for reducing environmental release of such contaminants and protecting surface water quality, and then public, animal and ecological health4. Thus, monitoring influent and effluent in municipal WWTPs[5,6], offers essential insights into its operational efficiency, enables wastewater surveillance (WWS) such as monitoring of pathogens circulating in communities[1,3,7], and assesses public, animal and ecological health risks from the pollutants releasing into receiving waters[4,7]. WWS is being used as an emerging approach for obtaining a real-time data on various pathogens, including SARS-CoV-2[8–10], polio virus[11–13], norovirus[14,15], mpox[16,17], influenza A[15,18], antimicrobial-resistant (AMR) pathogens[7,19,20] and illicit drugs[21] at a population level. It has also been employed to track dietary habits[22,23], community stress hormone levels[24,25], and exposure to organic pollutants[26].

A typical WWTP operates in three main stages: mechanical, biological, and chemical treatment (Figure 1). In the mechanical stage, large debris, sand, and heavy particles are removed using inlet screens, grit chambers, and primary sedimentation. The biological stage, often using the activated sludge method, employs microbes to break down organic matter, with nitrogen removal occurring in alternating oxygenated and non-oxygenated conditions, reducing nitrogen by 50–75% [27]. In the chemical stage, aluminum or iron compounds are added to precipitate phosphorus, which is removed as sludge[27]. Final clarification and filtration, often with sand filters, are used for stricter discharge requirements[27].

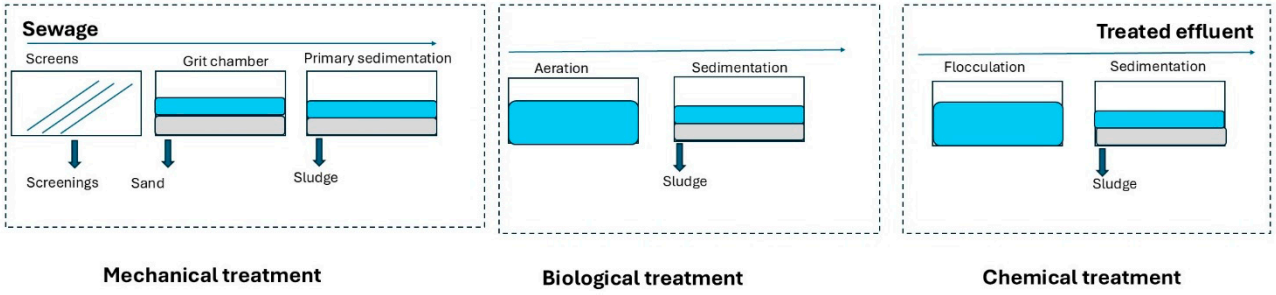

Figure 1. A typical wastewater treatment plant operates through three main stages: mechanical, biological, and chemical treatment.

While current WWTPs are primarily designed for removing nutrients like nitrogen and phosphorus to curb eutrophication, they are also able to significantly reduce anthropogenic contaminants and pathogens depending on their design and operations. Still, treated effluent often contains substantial amounts of pathogens, AMR organisms, AMR genes (ARGs), and a wide range of micropollutants including antibiotic residues and microplastics[4,6,21,28]. Thus, WWTPs are significant point sources of various chemical and microbial pollutants to recipient surface water]4,6]. Biological treatment units in WWTPs can become hotspots for AMR spread due to the horizontal transfer of ARGs[29,30]. Such transfer is exacerbated by various pollutants and microbial stress factors like microplastics, pharmaceuticals, and heavy metals[30,31].

The recast of European Union Urban Wastewater Treatment Directive 2024/3019 (UWWTD) broadens monitoring requirements for pathogens including AMR in wastewater [32]. The Nordic countries, as EU/EEA members, fully adhere to the recast of UWWTD. Their shared socioeconomic and climate characteristics support for the development of Nordic-specific guidelines for sustainable sanitation practices and a unified WWS approach to align with the directive, through regional collaboration[6,33]. This study used a Webropol survey of Nordic environmental authorities and thematic analysis of responses together with systematic review of peer-reviewed literature, and review of government reports and EU portals to examine WWTP coverage and treatment processes in Nordic countries.

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2. Methodology

A Webropol survey was conducted in July–September 2024, targeting environmental authorities, wastewater experts, and policymakers across Nordic countries. The survey collected data on centralized sewerage coverage, treatment methods, and operational challenges (Supplemental File). Survey was conducted in English, and used simplified, multiple-choice questions, each accompanied by a free-text field for additional input. Participants were assured of data confidentiality and anonymity, with participation being voluntary. To increase the response rate, we sent multiple reminders to invited respondents during the three-month survey period. The survey data from all countries underwent qualitative thematic analysis, categorized by country.

Further, survey response was supplemented with systematic review of literature of peer-reviewed journal articles, review of government reports and information from EU portals. Peer-reviewed papers were searched on Google Scholar using the following keywords: Wastewater, Sewage, and Sanitation combined with Finland, Denmark, Sweden, Norway, Iceland, Greenland, Åland, Faroe Islands, and Nordic. As we did not receive any responses from Danish participants, our reporting in Denmark relies entirely on secondary sources. Also, our reports regarding Greenland and Åland also fully relies on secondary sources.

3. Results

3.1. Webropol Survey

Six eminent representatives from various Nordic entities participated in the study. Finland had two respondents: one from the Environmental Ministry (policy level) and another from the Finnish Environment Institute. Sweden's data came from a national association, also at the country level. In Norway input came from a WWTP representing Rogaland County. In Iceland, a national authority responded at the country level. No response was received from Denmark. The Faroe Islands (Danish autonomous region) contributed through a governmental entity. This diverse group provides a broad perspective on wastewater treatment practices across Nordic regions and organizations. Responses of the survey are summarized in Table 1.

Table 1. Summary on response to Webropol survey.

Country	Population (growth rate prediction in 2024)	Number of cities with a population of over 20,000; and over 5,000	Total number of centralized WWTP	Number of WWTP with primary treatment	Number of WWTP with primary and secondary treatment	% of population coverage	The principle of WWTP establish	Majorly drive for treatment plant establishment	Major challenges in centralized WWTPs	Others

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Finland (EU-member country)	5.62 million (0.29 %)	56; 209	360	100 %	100 %	89	Legislation, population size, industrial needs, and protection of vulnerable areas like ground water sources.	Waste water treatment in Finland is regulated by the EU Urban Waste water Treatment Directive, the National Environmental Act, and municipal laws.	Aging infrastructure.	Finland has 100 % sanitation coverage
Iceland (EEA-member country)	0.39 million (1.51 %)	3; 8	15	80	4	90	Legislation, population size, industrial needs, and protection of vulnerable areas like ground water	Waste water treatment in Iceland is regulated by the EU Urban Waste water Treatment Directive.		Local cold climate & oligotrophic Atlantic justify the lack of WWTPs. The government subsi

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							sources.			dizes WWTPs in small cities.
Norway (EEA-member country)	5.59 million (1.04 %)	25; 91	16	100	90	-	Legislation, population size, industrial needs, and protection of vulnerable areas like ground water sources.	EU Urban Waste water Treatment Directive & National Pollution Control Regulations but lacks specific local regulations for smaller plants.		Local cold climate & oligotrophic Atlantic justify the lack of WWTPs.
Sweden (EU-member country)	10.61 million (0.53 %)	78; 272	1700	100	100	90	Legislation, population size, industrial needs, and protection of vulnera	The EU Urban Waste water Treatment Directive, National Pollution	Small sewage volumes and limited budgets are major challenges in small	Sweden adheres to the ***Polluter Pays*** principle uniformly

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							ble areas like ground water sources	Control Regulations, and local permits &, regional conditions.	communities.	across all WWTPs.
Faroe Island (Do not comply with EU rules and regulations)	55,400 (1.25 %)	1; 2	Does not have any modern treatment plants and sanitation is managed by septic tanks.	-	Environmental regulations are relatively soft, guided by national Law.		Population and national environmental regulations.	National environmental regulations.	Lack of strict environmental law, limited municipal budgets, low population coverage, & oligotrophic Atlantic as cost-effective dilution.	-

Coverage of Centralized Wastewater Treatment Plants

The first survey question addressed the coverage of centralized WWTPs in each respondent's country. The Finnish respondent reported approximately 360 centralized WWTPs serving 89% population in Finland, while the Swedish respondent noted around 1,700 WWTPs in Sweden serving 90% population. The Norwegian respondent, representing a regional level, reported 16 centralized WWTPs in their region. The Icelandic respondent mentioned 15 WWTPs in Iceland. There was no response from mainland Denmark, but the autonomous Faroe Islands reported a lack of fully operational WWTPs in their region. Faroe Island relying on decentralized systems such as septic tanks and larger tanks that separate solids from liquids, allowing natural degradation as a basic form

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of treatment. The major reason for not having WWTPs was mentioned not having legislative requirement, as it is not a part of EU/EEA and not bound by EU directives. Discharges from these systems are carefully managed by limiting the number of discharge points to minimize environmental impact.

Treatment Processes in Centralized Wastewater Treatment Plants

Regarding treatment processes in WWTPs, respondents from Finland, Sweden, Norway, and the Faroe Islands reported 100% primary treatment coverage, while Iceland reported 80%. Finland's primary treatment includes grit removal and screening, Norway uses coarse screening and filtration, and Faroe Islands employs screening, sedimentation, and solid-liquid separation. Sweden and Iceland did not specify their primary treatment processes.

For secondary treatment, Finland and Sweden have 100% coverage, the surveyed Norwegian region has 90%, Iceland has 4%, and the Faroe Islands lack secondary treatment. Finland uses activated sludge, biological filters, membrane bioreactors, and moving bed biofilm reactor systems, while Norway employs activated sludge and sequencing batch reactor processes. Sweden, Iceland and the Faroe Islands did not provide details on secondary treatment.

In tertiary treatment, Sweden has 98% coverage, Finland 10%, and the surveyed Norwegian region, Iceland, and the Faroe Islands have no tertiary treatment. Sweden primarily removes phosphorus (98%) and nitrogen (67%), with limited UV treatment. Finland employs sand filters, biological filters, membrane filtration, and UV disinfection. Sweden has 2% quaternary treatment coverage, using ozonation or granulated activated carbon filters. Finland, Norwegian region, Iceland, and the Faroe Islands do not have quaternary treatment. The Finnish respondent noted that the absence of tertiary treatment is due to the lack of specific legislative requirements, though it is common in some plants where stricter effluent limits apply. In Iceland, high costs and minimal environmental benefits in the oligotrophic Atlantic Ocean deter advanced treatment. The main barriers to advanced treatment include the absence of legal requirements, particularly in the Faroe Islands and small communities in all countries below population thresholds, and economic constraints.

Legislative Provisions for Wastewater Treatment Plant Construction

At the time of survey, the recast 2024/3019 of UWWTD was not yet in force. In the Nordic countries, EU/EEA respondents cited the earlier UWWTD version (EEC 1991) as the primary legislation governing wastewater treatment coverage and operations, except for the Faroe Islands, which is not part of the EU/EEA agreement. In addition to the UWWTD, Finland follows the Environmental Act and the Government Decree on Urban Wastewater (Valtioneuvoston asetus yhdyskuntajätevesistä), particularly for small communities. Local regulations determine permit conditions, and WWTPs must submit annual reports to obtain environmental permits from local authorities.

Sweden responded to adhere to the UWWTD (1991) along with other directives influencing wastewater treatment, including the Water Framework Directive (WFD), Environmental Quality Standards Directive (EQSD), Groundwater Directive (GWD), and Bathing Water Directive (BWD). National regulations are based on the Environmental Code (Miljöbalken), with stricter local regulations depending on regional conditions. In Norway, the national framework is set by the Pollution Control Regulations (Forurensningsforskriften). However, there is a lack of comprehensive local regulations for monitoring smaller treatment plants. Iceland reported no municipal wastewater regulations. The Faroe Islands have independent wastewater regulations, where wastewater management is governed by national legislation, with municipalities responsible for implementing guidelines under the Faroese Environmental Agency.

Respondents' Perception on the recast of European Union Urban Wastewater Treatment Directive, 2024

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Regarding respondents' perceptions of the upcoming recast of EU UWWTD, the Finnish respondents expressed a generally positive view of the revision. They noted that over the next 20 years, nitrogen removal limits will tighten, requiring tertiary filtration or equivalent post-treatment. Micropollutant removal was awaited to improve effluent quality from larger plants, with membrane technology expected to play a larger role in plant renovations. While this was seen as beneficial for maintaining high environmental standards, costs remain as a concern.

The Swedish respondent highlighted the recast of UWWTD, along with the new environmental quality standards directive (EQSD) and groundwater directive (GWD), will introduce significant changes, particularly with the introduction of quaternary treatment. The responded stated that about 50-100 WWTPs in Sweden will need to invest in this advanced treatment, and some of them will face stricter nitrogen removal requirements. It was also mentioned that Sweden's phosphorus removal standards are already stricter than those outlined in the new directives.

The Norwegian respondent shared a generally positive outlook on the revision but emphasized the need for adjustments based on local conditions, such as small populations and cold climates. They noted that the most significant change will be the requirement for quaternary treatment investment in some WWTPs. However, they cautioned that the environmental benefits of stricter treatment standards must not be outweighed by costs, including energy and resource consumption.

The Icelandic respondent pointed out that the proposed revisions fail to consider Iceland's unique geographical and environmental context, such as small populations and cold climates, which could make meeting the increased treatment requirements challenging. The Faroe Islands respondent mentioned, the revisions to the EU directives may indirectly influence their practices, encouraging stricter national standards for treatment processes and discharge quality.

Key Criteria for establishing Wastewater Treatment Plants

Regarding the key criteria for establishing WWTPs, Finnish and Swedish respondents emphasized majorly compliance with legislative requirements, population size, industrial needs, proximity to other plants, and the protection of vulnerable areas such as groundwater and environmental sensitivity of recipient water. In sparsely populated areas, smaller sewage volumes, limited budgets, and low environmental vulnerability make building modern treatment plants challenging, with low chances for central grants. Smaller municipalities, with populations about less than 20,000, face challenges in financing, staffing, and securing qualified engineers. Respondent agreed, in the Norwegian region, WWTP establishment is influenced majorly by population size, and others are proximity to other plants, environmental protection, and legislative requirements.

Finland and Sweden emphasized that all wastewaters must be treated, with municipalities defining operational areas according to national water supply laws. However, operating full-scale traditional WWTPs is economically and practically challenging when there is no environmental or health risk, typically for smaller municipalities (population < 25 households). Iceland and Norway cited sparse populations as a challenge for establishing treatment plants, while the Faroe Islands pointed to low population density, economic factors, environmental impact, and regulatory guidelines.

The absence of developed WWTPs in the Faroe Islands is attributed to a lack of legislative requirements, economic constraints, and a perceived low environmental risk. As the Faroe Islands are not part of the EU or the EEA, EU directives, including the UWWTD, do not apply.

Financing of Treatment Processes

In Finland and Sweden, all WWTPs operate based on user fees following the "polluter pays" principle. Norway finances wastewater treatment through municipal taxes based on the load, with all municipalities adhering to the same rules. In Iceland, the government can provide subsidies to communities for establishing and upgrading treatment plants to maintain environmental standards. In the Faroe Islands, municipalities are responsible for financing wastewater treatment through a portion of collected taxes, with no direct charges to residents.

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3.2. Systematic Review of Peer-Reviewed Articles, Government Reports and European Union Online Portals

Our systematic review did not find any literature about the coverage and treatment technologies on centralized WWTPs in Nordic countries. Few research focused on decentralized treatment coverage and technologies (e.g., Table 2). We found about coverage and treatment technologies of WWTPs in government reports on respective countries and also in portals of European Union. Finnish Environment Institute (SYKE) reported Finland has around 350 municipal WWTPs serving populations over 100 and requiring environmental permits from local authorities[34]. Swedish EPA reported 429 WWTPs in Sweden[27], among them a total of 255 plants using both biological and chemical processes, 41 focused on phosphorus removal, 2 relied on biological treatment, and 109 included biochemical nitrogen removal [27]. According to the Norwegian Environment Agency (NEA), Norway has around 2,500 municipal WWTPs, with 400 holding discharge permits from County Governors [35]. Danish Environmental Protection Agency (DEPA) reported Denmark has over 1,000 WWTPs [36].

We found a EU portal Eurostat reported, sewage networks with at least secondary treatment covered 85% of Finland, 96% of Sweden, 71% of Norway, and 98% of Denmark's population in the year 2022 [37]. Sanitation coverage in Nordic countries were reported exceeding the EU average of 81 % with at least secondary treatment[37]. The Eurostat portal does not report the prevalence of secondary treatment plant coverage in Iceland. Next EU WWTP portal reported a total of 1,239 WWTPs, serving populations of over 2,000 equivalents, across the five Nordic countries, with Sweden having the highest number (428), followed by Denmark (330), Norway (318), Finland (146), and Iceland (17)[38] (Table 3).

Decentralized Sanitations in Nordic countries

In Nordic areas without centralized treatment, various decentralized solutions are used[43–45]. In Finland and Sweden, remote households, summer cottages, and small coastal settlements—particularly on islands—typically use small onsite treatment systems, ensuring nearly 100% sanitation coverage. Common methods include on-site systems for single or small groups of households, small water associations (serving under 100 residents) practice holding tanks, soil treatment systems (e.g., filtration, sand filters, infiltration fields), package plants, and wetlands (e.g., willow systems) [43–45]. Source separation systems and dry toilets are used in some leisure homes but are rare in permanent residences[43]. Constructed wetlands, for example, are favored for their simplicity, low cost, and minimal maintenance, enhancing water quality and protecting ecosystems before discharge into lakes and rivers[46].

As of 2015, the Danish Environmental Protection Agency (DEPA) reported about 281,500 properties not connected to a centralized sewage system [36]. In Denmark, wastewater discharge requires a permit with limits on volume and pollutants, and harmful discharges are prohibited [36]. DEPA regulates permits, compliance, and discharge conditions [36]. Municipalities manage sewers, pump stations without overflow, and related infrastructure, ensuring functionality and monitoring water quality [36]. Wastewater utilities establish, operate, and maintain public sewage systems up to property lines, including wastewater and, in separate systems, rainwater treatment [36]. Norway also has ~350,000 small treatment units, serving ~800,000 PE in rural areas or cabins, while ~500 untreated discharges from ~350,000 PE require new plants[35]. A trend toward connecting individual systems to centralized networks is continuously increasing in Norway.

Literature review shows that, Greenland, a Danish autonomous region, follows varied wastewater management approaches[42]. For example, Sisimiut, the second largest city in Greenland, about 1,200-1,300 homes drain sewage directly into the ocean; around 500 homes dispose of wastewater into the ground; another 500 homes use tanks that are emptied into the ocean; and about 300 homes use honey buckets, with waste discharged into the sea [49,50].

4. Discussion

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This study assessed the status of centralized WWTPs in Nordic countries from the perspective of WWS, an emerging epidemiological surveillance approach. It found ~85-90% of the Nordic population is connected to centralized WWTPs, making WWS highly feasible. The article 17 in recast of EU WWTD 2024/3019, mandates adoption of AMR monitoring in treatment plants serving over 100,000 people[32]. So far, WWS has been piloted to track various AMR pathogens[20,52] and antibiotic resistance genes[53].

Our survey found, in Sweden and Finland, all WWTPs have primary and secondary treatment; in the region of Norway, 90% and Iceland, only 4% were reported having both primary and secondary treatment. In Finland, wastewater must be treated before being discharged into surface waters or the environment[34]. Regarding, small settlements in Norway and Iceland, particularly along the coast, residents either rely on private systems or have no treatment facilities, leading to direct discharge into the open Atlantic Ocean[47,48]. Unlike the Baltic Sea, the northern Atlantic is oligotrophic, meaning moderate nutrient discharges are easily diluted unless they cause aesthetic concerns.

While comparing the WWTPs numbers from our survey with other sources (national reports or EU portals), we found highly variation on numbers, indicating lack of universal definition of WWTP. While talking WWTP, context matters—whether considering only full-scale plants, those meeting the 1991 UWWTD, or small units following local rules. Some literature even defines WWTPs as single-household systems (e.g. composting toilets)[43]. For our purposes, any facility collecting wastewater from multiple households and pooling community wastewater qualifies as a wastewater facility for WWS. Contradicting, all other sources and our survey response, a master thesis conducted in University of Iceland reviewed, in the eastern cities of Iceland, 66% of wastewater undergoes stricter treatment, such as UV post-treatment in Egilsstaðir and Mjóifjörður[54]. In the South, Hveragerði and Hvolsvöllur have secondary treatment, while Hella uses primary treatment[54].

Major driving factor for establishing the WWTP is environmental protection needs, influenced by political, economic, and legislative factors, and typically depends on population size, industrial activities, and environmental goals. Treatment intensity is influenced by the sensitivity of receiving water bodies. In coastal cities along the North Atlantic in Norway and Iceland, where conditions are less vulnerable, wastewater is often partially treated[33,47,55]. In Finland, Sweden, and Denmark—where the Baltic Sea is highly sensitive—more effective wastewater management is prioritized [56]. The vulnerability of inland rivers and lakes to pollution has led to advanced treatment processes in local WWTPs[4,57]. EU directives impose relatively stricter rules for inland waters than coastal areas, as freshwater is vital for irrigation, drinking water, and industry, requiring greater protection[32,58–60]. In contrast, coastal wastewater discharge benefits from ocean dilution, and saltwater's natural biocidal properties [48]. Regional differences also matter—the eutrophication-prone Baltic Sea demands stricter nutrient controls than the more oligotrophic Atlantic, where human-derived nutrients dilute more easily. Economic and technological factors further shape WWTP installation, including infrastructure investment, advanced treatment costs, and the feasibility of centralized systems in small communities.

Our study found at least 15% of Nordic areas, majorly remote regions and holiday homes, lack centralized sewage connections. Artic communities face unique challenges for establishing WWTPs due to harsh Arctic climate, permafrost, and cold temperatures. Factors like dispersed populations, flooding during spring due to snow melt, and high fuel costs add complexity, increase infrastructure costs, and complicating biological treatments like nitrogen removal[33,42,45]. In addition, Greenland and the Faroe Islands face greater obstacles due to weak regulations, economic constraints, and limited funding. Geography also impacts for establishing centralized WWTPs—Norway, for instance, is 44% mountainous, 38.2% forested, and 13% covered by glaciers, wetlands, and lakes, leading to low centralized sewer coverage[45]. The 1991 UWWTD exempted settlements under 2,000 inhabitants from centralized WWTP requirements, with the 2024 revision lowering this to 1,000[32].

Our survey respondent noted that the Faroe Islands rely on septic tanks and lack WWTPs, as they are outside the EU/EEA and not bound by EU directives. Similarly, Greenland, a Danish

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autonomous region, follows varied wastewater management approaches lacking centralized treatment options[42’49,50].

In most Nordic areas (mainly in EU/EEA) without centralized treatment, various decentralized solutions have been used for maximizing the sanitation coverage[43–45]. Common practices are holding tanks, soil treatment systems (e.g., filtration, sand filters, infiltration fields), package plants, and wetlands (e.g., willow systems), constructed wetlands[43–46]. A trend toward connecting individual systems to centralized networks is continuously increasing in Norway[47]. National regulations cover all treatment facilities, including small agglomerations outside the directive’s scope, enforcing stricter treatment for sensitive waters[47]. Norway’s northern Atlantic waters are oligotrophic and less sensitive to phosphorus and nitrogen, favoring mechanical treatments like screens[47]. These primarily improve aesthetics, as nutrient loads from small populations dilute quickly in the ocean. National regulations ensure cost-effective solutions for agglomerations under 2,000 PE, aligning with the directive and Water Framework Directive obligations[47].

Discharging untreated wastewater contributes to eutrophication, particularly where water exchange is poor, and introduces organic chemicals, including medicine residues, that can accumulate in the food chain, disrupt endocrine functions, and promote antibiotic resistance. Polluted water degrade fish and seafood quality, due to containing harmful microorganisms[41]. In cold climates, pathogens may persist longer due to low temperatures and snow cover[61]. However, a previous study reported, partially treated or raw sewage discharged into the Arctic Atlantic posed minimal pollution issues, as the ocean pose high turbulence so easily diluted [42], except for some emerging pollutants in coastal areas with limited water circulation[33,40,48].

Existing challenges for centralized sanitation in Nordic countries include aging infrastructure and distribution networks in larger cities, leakage reduction, rapid urban growth, and combined sewer overflows39. Smaller cities face challenges due to limited budgets, low sewage volumes, and decreasing populations40,41. Northern and Arctic cities face issues related to dispersed populations, harsh climates, permafrost, long coastlines, hard rock surfaces, and spring flooding[6,33]. In remote areas outside the EU/EEA, the absence of stringent environmental regulations, economic constraints, limited municipal funding, and sparse populations pose additional challenges[40,42].

5. Conclusions

A Webropol survey and literature review show that 85–90% of the Nordic population is connected to centralized WWTPs, demonstrating the feasibility and cost-effectiveness of WWS for public health. WWS enables comprehensive health monitoring in urban areas by analyzing a single wastewater sample. Further it found, Finland, Denmark, and Sweden enforce strict WWTP permits and effluent standards to protect sensitive ecosystems like the Baltic Sea. In contrast, many coastal areas in Norway and Iceland have less stringent regulations, with small communities discharging partially treated sewage into the Atlantic. Remote and mountainous regions pose additional challenges for centralized sewage networks, leading some communities to discharge wastewater even untreated, while many others use decentralized treatment options.

Table 2. Literature obtained from systematic review discussing various aspects of WWTPs coverage and process in Nordic countries.

SN	Study type	Study type	References
1	Review	The establishment and evolution of urban and rural water systems in Finland showcase a remarkable journey of innovation, institutional diversity, and trust-building. Over just two decades, Finland achieved efficient water pollution control by implementing advanced technologies and progressive legislation,	Katko et al 2022 [39]

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		setting a global benchmark. However, the nation now faces the pressing challenge of aging infrastructure, requiring innovative solutions and updated standards to maintain sustainability. The Finnish experience highlights the importance of continuous development and integrated approaches, offering valuable lessons for sustainable water management and future policymaking worldwide.	
2	Original paper (Finland & Sweden)	Many rural areas in Nordic countries rely on onsite treatment systems, though their efficiency varies widely. Phosphorus removal typically also reduces microbial loads in treated wastewater.	Heinonen-Tanski & Matikka 2017 [44]
3	Review	The study assessed on-site WWTP performance in Finland and Sweden, reviewed 1301 samples from 395 units across 10 studies. It revealed significant variability in treatment outcomes and emphasized the need for innovation and regulatory improvements for sustainable wastewater management.	Kinnunen et al. 2023 [55]
4	Original paper (Sweden)	Constructed wetlands are commonly used in Sweden for the further treatment of effluent from WWTPs. These wetlands, featuring diverse vegetation and algae, treat the remaining nutrients and suspended particles in the wastewater. The refined water is then discharged into surface water bodies.	Andersson et al. 2005 [46]
5	Review paper (Norway)	Norway's unique landscape—comprising mountains (44%), forests (38.2%), and freshwater, glaciers, and wetlands (13%)—limits the use of centralized sewerage systems, leaving a large population without access to them. In some areas, decentralized constructed wetlands have been adopted as an alternative treatment option.	Paruch et al 2011 [45]
6	Original study in Greenland	Sewage in Greenland is inadequately treated, contributing to plastic pollution in the Arctic marine environment.	Bach et al. 204 [40]

Table 3. Entering load (population equivalent) and the number of active wastewater treatment plants by type in 2020, serving a population over 2,000 equivalents in Nordic countries[38].

Country	Treatment types	Total capacity (population equivalent)	Generated and entered plants (population equivalent)	Entering load (population equivalent)	Total Number of Plants
Denmark	NP removal	11 792 195	11 729 212	7 315 084	261

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	Phosphorus removal	245 539	251 773	122 386	55
	Other treatment	3 000	2 000	1 827	1
	Secondary treatment	42 600	43 610	18 269	13
	Total	**12 083 334**	**12 026 595**	**7 457 566**	**330**
Finland	NP removal	4 040 900	3 165 937	3 987 100	37
	P removal	3 269 350	2 387 563	288 050	109
	Total	**7 310 250**	**5 553 500**	**6 867 150**	**146**
Iceland	Other treatment	82 330	80 373	63 712	8
	No treatment	640 500	428 468	430 596	9
	Total	**722 830**	**508 841**	**494 308**	**17**
Norway	NP removal	1 535 570	1 910 824	186 4841	6
	Phosphorus removal	2 888 802	3 160 215	2 867 078	151
	Secondary treatment	970 860	1 072 733	1 261 222	13
	Primary treatment	1 358 383	1 440 331	1 305 402	148
	Total	**6 753 615**	**7 584 103**	**7 298 543**	**318**
Sweden	NP removal	11 230 759	10 082 800	8 779 682	145
	P removal	3 277 630	2 732 930	2 244 622	283
	Total	**14 508 389**	**12 815 730**	**11 024 304**	**428**
Pooled all Nordic countries	NP removal	28 599 424	2 688 8773	21 946 707	449
	P removal	9 681 321	8 532 481	8 114 136	598
	Other treatment	85 330	82 373	65 539	9
	Secondary treatment	1 013 460	1 116 343	1 279 491	26
	Primary treatment	1 358 383	1 440 331	1 305 402	148
	No treatment	640 500	428 468	430 596	9

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	Total in Nordic countries	**41378418**	**38488769**	**33141871**	**1239**

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