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Review

Sustainable Valorization of Drinking Water Treatment Sludge: A Review

Mohamed Bensaddik [1,2], Nihade Bensitel [1], Chaimae El Yaacoubi [1], Yahya El Hammoudani [1,*], Fatima-Zahra Azar [1,2] and Achraf El Kasmi [1,*]

[1] Laboratory LSIA, ENSAH, Abdelmalek Essaadi University, Al-Hoceima 32003, Morocco; nihade.bensitel@etu.uae.ac.ma (N.B.)
[2] Department of Chemical and Biochemical Sciences (CBS), Mohammed VI Polytechnic University (UM6P), Benguerir 43150, Morocco
* Correspondence: y.elhammoudani@uae.ac.ma (Y.E.H.); a.elkasmi@uae.ac.ma (A.E.K.)

Abstract

Among the critical stages in the drinking water treatment process is the coagulation and flocculation stage, during which a non-sustainable coagulant, such as aluminum or iron sulphate, is added to remove the dissolved and suspended components from the water. This generates a byproduct known as drinking water treatment sludge (DWTS). Alum sludge is the most commonly produced, which causes economic and environmental challenges that must be considered to bridge the gap between water treatment processes and generated sludge management. Recent research focuses on the reuse of DWTS in various fields to avoid its direct disposal and environmental impacts. This review aims to evaluate the valorization of drinking water treatment sludge as a sustainable product in a circular waste management approach, by assessing its potential to be used especially in agriculture for soil restoration and in adsorption, in attempts to evaluate the potential reuse of DWTS as a sustainable and alternative solution. Some challenges related to structure and potential ecological risks are comprehensively discussed with a focus on the crucial role of this sludge. Furthermore, techno-economic aspects were considered for assessing the technical and economic feasibility of DWTS. Research priorities and future challenges that will enable exploration and innovation in sludge reuse across many aspects were also discussed.

Keywords: drinking water treatment sludge; alum sludge reuse; agriculture applications; CO_2 adsorption; waste valorization; sustainable management; techno-economic aspects

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1. Introduction

Clean and safe drinking water is a basic human right and an essential ingredient of sustainable development. Yet, water production is increasingly threatened by a combination of global and local drivers, including population growth, climate change, and water resource pollution [1,2]. As the world's population is increasing and is estimated to reach close to 10 billion by 2058, the demand for potable water has increased sharply, especially in urban areas where existing infrastructure often operates at full capacity [1]. Such rapid urbanization, combined with the intensification of industrial and agricultural activities, has subjected freshwater resources to unprecedented pressure, with many becoming contaminated or overexploited. For example, in North Africa and the Middle East, water shortages are aggravated by arid climatic conditions and low rainfall, rendering effective management and recycling of water resources a survival issue [3]. What further worsens the situation is the

widespread pollution of surface and groundwater resources. Industrial wastewater, agricultural runoff with pesticides and fertilizers, and raw sewage have immensely degraded water quality in most regions of the globe. Specifically, in Morocco, the Inaouene River, which is one of the most important water supplies of the Idriss 1st Reservoir, has been found to have excessive chemical oxygen demand (COD) and chlorides from unprocessed domestic wastewater and agricultural runoff [4]. This type of pollution not only complicates treatment processes but also increases the volume of sludge generated, as more impurities are extracted from water. In a bid to overcome these issues, water treatment facilities depend on traditional processes, which include coagulation, flocculation, sedimentation, and filtration. Coagulation and flocculation are particularly important methods for removing suspended matter, organic material, and disease-causing microbes from surface water, including raw water. Coagulation involves the addition of chemicals, such as aluminum sulfate (alum) or ferric chloride [5]. They neutralize the negative charges on the suspended material, allowing for these materials to flocculate more readily into larger flocs. These flocs are then removed during sedimentation and filtration, improving water quality [6]. Although very effective, these processes also produce a significant amount of sludge as waste. The target sludge is composed of solid particulate material eliminated in the treatment process, together with absorbed minerals, humic material, and residual coagulants [7]. The sludge composition is different based on the quality of influent water and the type of coagulant used but generally contains high amounts of aluminum or iron hydroxides, organic matter, and trace quantities of heavy metals [8].

Italy produces over 750,000 tons of sludge from its water treatment plants every year. Quite a sizable fraction of it is landfilled or incinerated [9]. The annual sludge production in the United States (U.S.) is estimated to be about 35–40 million metric tons of dry sludge from drinking water treatment plants over the period 2000–2015, estimated from sludge generation factors [10]. In the developing world, where regulatory frameworks and infrastructure are often severely lacking, the case for and methods of sludge disposal rarely find validity; open dumping or direct discharge into water courses has been the most accepted practice for many plants, exposing the environment and public health to tremendous risks. Alum sludge, which results from the utilization of aluminum sulfate, is the most prevalent sludge produced across the globe owing to the extensive application of alum as a coagulant [7,8]. The popularity of alum may be attributed to its high efficiency in turbidity as well as pathogen removal, coupled with its relative affordability.

Nevertheless, its application generates sludge high in aluminum hydroxide and other minerals, making its management difficult. Conventional disposal practices, including landfilling and incineration, are not only expensive but also present serious environmental hazards. Landfilling may result in the leaching of heavy metals and other pollutants into the soil and groundwater, whereas incineration results in the emission of greenhouse gases and other pollutants into the atmosphere [11]. The high-water content of sludge, which is usually more than 80%, makes it bulky and costly to transport, hence compounding disposal issues [12]. The solids content in the alum sludge (thickened sludge) reaches 2–4%, 17–23% for mechanically dewatered (centrifuged) sludge and 50–70% in drying beds [13]. Comprehensive statistics on this have not been available, owing to variations in the nature and quantity of the sludge in various treatment works, coupled with climatic conditions. In the southern part of Italy, six drinking water treatment plants, specifically Sinni, Pertussillo, Fortore, Locone, Camastra, and Metapontino, produce about 70 tons per day of sludge, corresponding to a total of about 25,200 tons per year [14]. On the other hand, in Portugal, the yearly production of water treatment sludge is estimated to be around 66,000 tons/year (wet weight) [15]. Moreover, the economic costs associated with the disposal of the sludge should also be considered [13].

To counter these losses and optimize the use of this residue, the administration of DWTS has risen as a key avenue in water treatment plants around the globe due to conflicting pressures for environmental preservation and economic viability. Traditional disposal techniques, such as landfilling and incineration, are increasingly regarded as unsustainable due to the associated costs, environmental threats, and legislative limitations [11,16]. While landfilling is short of expensive, its long-term effects include possible groundwater contamination from leachate and emission of methane through anaerobic decomposition of organic waste [17]. Incineration, however, may reduce the volume of sludge but unfortunately involves considerable energy consumption and the release of greenhouse gases and toxic pollutants into the atmosphere. Taking these points into consideration, the increasing popularity of sustainable sludge management solutions highlights the complexity of producing value-added products from wastewater biosolids, as seen from a circular economy perspective. One of these routes of high potential for DWTS valorization is agriculture. Like other sludges used as soil amendments, which can supply nitrogen, phosphorus, and potassium to crops [18,19], DWTS contains these nutrients and is also able to retain nitrogen and phosphorus [20]. The use of DWTS in farming areas can impart structure to soil, water-holding capacity, and stimulation of microbial activity, ultimately leading to higher crop production and a decrease in the use of chemical fertilizers [11]. For instance, research indicates that the use of DWTS on sandy soils greatly enhances their moisture and nutrient retention capacity and hence makes the soils more productive for maize and wheat cultivation [21]. Nevertheless, the application of DWTS in agricultural systems is accompanied by certain challenges. The presence of heavy metals in sludge may compromise soil integrity, crop safety, and human health if not properly regulated. Heavy metal levels in alum sludge are generally below regulatory limits (below the TCLP regulatory limits), but they must be monitored because they vary depending on the nature of the raw water and the coagulant used [11]. To alleviate these risks, scientists have explored several pretreatment techniques, including thermal treatment [22], to minimize the bioavailability of heavy metals and ensure the safe application of DWTS. Other than its use in agriculture, DWTS has also demonstrated great potential as an economic adsorbent for CO_2 removal [23], for adsorption of nutrients, and for extraction of heavy metals, particularly those found in wastewater [22,24,25]. The evolution of research points to the fact that through thermal treatment and acid activation, the efficiency of DWTS can be enhanced to develop better adsorption properties and, therefore, a wider range of use [26]. The fact that DWTS features a great surface area and porosity, especially when thermally or chemically activated, makes it an effective material for the adsorption of heavy metals and nutrients [22,27]. DWTS, for example, has been successful in the removal of phosphorus from wastewater, thereby minimizing the potential eutrophication hazard in downstream aquatic ecosystems [27]. Its capacity to adsorb heavy metals like lead, cadmium, and chromium renders it a top option for the remediation of industrial effluents and polluted groundwater [16]. These uses not only address sludge disposal but also provide low-cost water and wastewater treatment solutions, particularly in resource-scarce settings.

Rising interest in recycling DWTS highlights the need for comprehensive techno-economic investigations to determine its feasibility and potential for enhancement. With the advantages of reuse through DWTS in environmental and agronomic aspects, wider implementation is tied to overcoming significant technical and economic barriers [21] and assessing the associated environmental risks [28]. The techno-economic analysis provides a framework for quantifying the costs, benefits, and risks of DWTS reuse so that relevant stakeholders can understand the basis for decisions to implement it. A techno-economic assessment takes into consideration elements including sludge composition, treatment needs, transportation costs, and revenue possibilities from resource recovery. This review

seeks to know the sustainable production of drinking water through conventional methods and green technologies for drinking water treatment, and on the other hand, to understand the characteristics of current DWTS, and to determine the possibility of reusing DWTS in agricultural applications to understand how it affects the soil and nutrients, and its role in adsorption processes, in addition to the technical and economic study that also includes the strengths and weaknesses associated with drinking water treatment sludge.

2. Management of Drinking Water Treatment Sludge

2.1. Global State of Drinking Water Production

Drinking water production is found in the use of both surface and ground water sources, which are under increasing stress at the source due to population growth, economic expansion, and climate change impacts [1,2]. Rainfall is the primary contributor to water resources, but rain occurs in part and often differs considerably from year to year [3]. Groundwater in rural areas is considered the source of drinking water [29]. There is a problem of pumping this water and its overexploitation, which makes water extraction faster and affects its natural recharge [30–32]. Even in those areas that have piped water, point-of-use treatment is warranted, since bacteria could cause a recontamination of clean water [33]. Millions of people remain without access to safe drinking water in rural areas where groundwater quality does not meet health parameters [34]. Water production status is characterized by a high degree of dependence on surface and groundwater resources, both subject to acute pollution, overexploitation, and the effects of climate change [29,35].

About 2 billion people still do not use managed drinking water safely [2]. Three billion people, 40 percent of the world's population, do not have a place in their homes where they can wash their hands with soap and water. More than 600 million people will lead healthier lives by 2023, due to improvements in water and sanitation services [36]. The availability of safe drinking water remains a global problem despite the efforts made to advance it. Although the percentage of the world's population with access to drinking water increased from 69% to 73% between 2015 and 2022 (Figure 1), the use of basic drinking water services reached at least 91%, while 296 million people still depend on unimproved sources and 115 million on surface water [37].

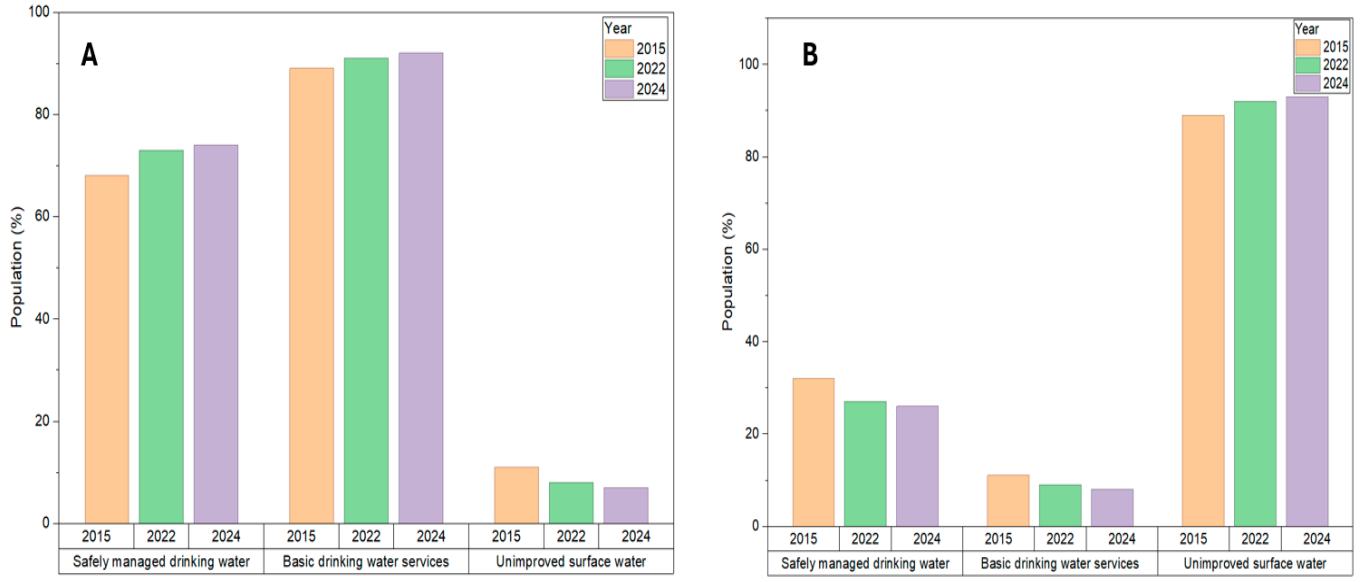


Figure 1. Trends in global access to drinking water services (2015–2024): (**A**) with access, (**B**) without access.

Management strategies differ, depending on the geographical region and local conditions. Despite physical and chemical water quality parameters in the Tano North Municipality of Ghana being largely within WHO guidelines, a typical example of the enhancement of point-of-use contamination is the presence of high levels of fecal indicator organisms shortly after withdrawal, coupled with improved physicochemical quality. In this context, a quantitative microbial risk assessment (QMRA), including the organization of follow-up samples, revealed public health implications and increased management vigilance to control those outbreaks more effectively [33]. In Iran, the incorporation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI), modified to local conditions, has been used for water management efforts, making an asset available as a flexible tool for rural water resources [38].

Drinking water treatment has relied on processes like coagulation, flocculation, sedimentation, filtration, and disinfection. These methods are rooted in basic physical and chemical principles that aim to remove turbidity, pathogens, and suspended solids. Coagulation and flocculation involve adding chemicals, such as alum, to aggregate fine particles into larger flocs that settle during sedimentation (Figure 2). Filtration, often through sand or other granular media, further removes impurities, while disinfection, commonly using chlorine, ensures microbiological safety [39,40]. But the presence of microplastics, bacteria, and viruses in drinking water systems is becoming a serious environmental problem [41]. Advanced drinking water treatment techniques are therefore required to improve water quality to a level suitable for human consumption [41,42], and also the widespread use of chemicals, pharmaceuticals, and personal care products (PPCPs), pesticides, and solvents made the adoption of advanced technologies necessary, because conventional DWTs were not designed to remove emerging pollutants [43,44]. This is further exacerbated by the increasing stresses on water resources due to population growth, deterioration of natural water resources, and heightened awareness of new EPs, which in turn leads to new standards and regulations covering more restrictive concentration levels. This situation has become more acute, creating opportunities for the development of advanced production technologies (summarized in Table 1).

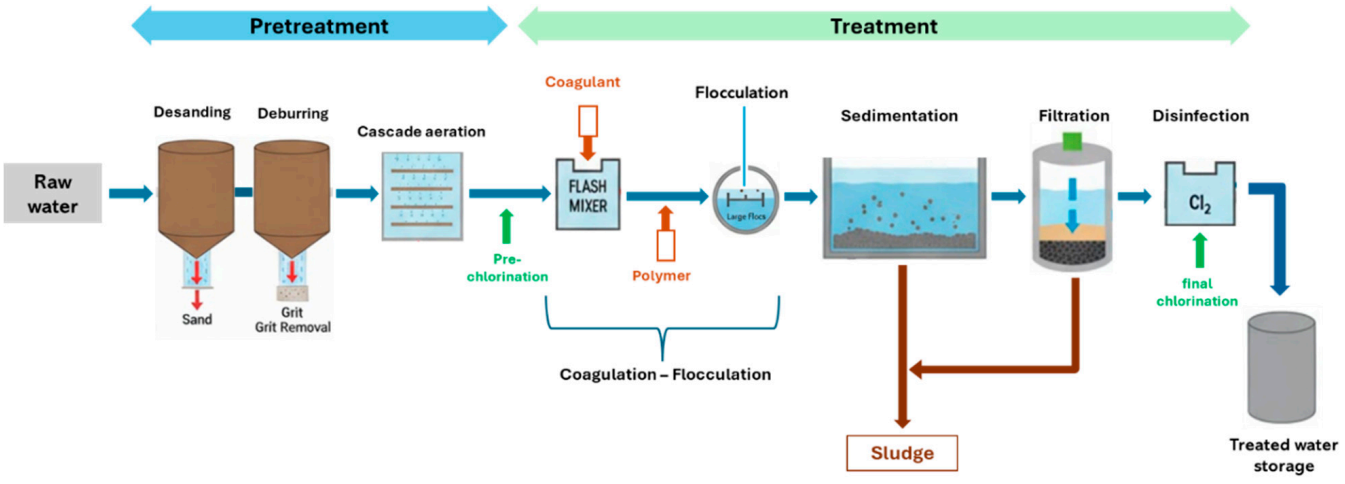


Figure 2. Schematic diagram of drinking water treatment process.

Table 1. Advanced methods of drinking water treatment.

Methods	Sub-Methods	Description	References
Solar disinfection technology	Semiconductor photocatalysis:	This method comprises the use of semiconductor materials such as titanium dioxide (TiO_2) to generate hydroxyl radicals, which can degrade organic contaminants and pathogens under UV light as the energy source of the photocatalytic process generated from natural sunlight. Hydroxyl radical (•OH) formation is well known to decompose various organic pollutants and pathogenic microorganisms with high disinfection potential.	[41,45–48]
	Dye photosensitization	Singlet oxygen thermokinetic stability, reactive oxygen species associated with the inactivation of pathogens in water. This method provides a solution to disinfection in regions of high solar radiation and aids in better pathogen removal.	[46,49]
	Ultraviolet (UV) irradiation using light-emitting diodes (LEDs)	These are integrated with photovoltaic panels to harness solar energy for UV-LEDs, used for targeted UV radiation on microorganisms. It has been observed that this technology has low energy consumption and is an efficient one for small volumes of water.	[46,49]
	Solar distillation	Solar distillation where we use solar energy to evaporate water, and the vapor comes in contact with a cool surface (or at night) for condensing it into purified water. This method is particularly useful for treating brackish or contaminated water sources. Solar stills are simple to construct and operate, making them suitable for use in remote or resource-limited settings.	[46,49]
	Solar pasteurization	This process destroys bacteria through thermal inactivation by raising the temperature of water to 75 °C with the help of the application of solar energy. This technique is well suited for small-scale applications in high-altitude sunny regions with no access to conventional energy supply. Solar pasteurization is a low-cost, sustainable alternative solution for water quality improvement in deprived areas.	[46,49]
Membrane filtration technologies	Microfiltration (MF) and Ultrafiltration (UF)	These processes are especially valuable in regions where raw water sources contain high levels of turbidity or biological contamination. Studies indicate that UF is highly effective in providing a reliable barrier against pathogens without the need for chemical disinfectants, thus minimizing chemical usage.	[50]
	Nanofiltration (NF) and Reverse Osmosis (RO)	RO becomes a vital desalination technique; NF membranes with somewhat larger pores than RO are employed for the separation of divalent ions and large organic molecules, providing a technological solution both to reduce water hardness and to preserve essential minerals. A push towards environmentally friendly and sustainable water treatment solutions, especially in the case of membrane technologies that are increasingly implemented with solar power today. Small membrane filtration systems powered by solar energy provide a scalable solution, making clean water more accessible in regions lacking reliable infrastructure.	[41,46,47,49]
	Hybrid membrane technologies	They represent a synergistic combination of membrane-based physical separation with chemical or photochemical reactions for the mineralization of stubborn pollutants such as bisphenol-A and haloacetic acids. As has been pointed out by Valdiviezo Gonzales et al. (2021), it would be possible to solve the complex problems generated by emerging pollutants and different qualities of water using various treatment technologies united in a single system.	[47,50]

Table 1. *Cont.*

Methods	Sub-Methods	Description	References
Advanced Oxidation Processes (AOPs)	Hydroxyl Radical-Based AOPs	UV/H_2O_2 processes are frequently used in drinking water treatment to successfully degrade micropollutants. In addition, the combination of UV–ozone (UV/O_3) has proven effective for the generation of hydroxyl radicals capable of mineralizing complex organic molecules. A typical example of AOP is photocatalysis, using titanium dioxide (TiO_2) as an effective catalytic agent when irradiated with UV light. Given that TiO_2 photocatalysis can degrade organic pollutants, etc., the TiO_2 photocatalytic degradation of pollutants technology becomes another effective tool for the elimination of emerging contaminants and environmental protection.	[41,46,47,49]
	Ozone-Based AOPs	Ozonation is particularly effective for the degradation of organic compounds and disinfection of water. When combined with UV or hydrogen peroxide, ozonation enhances the production of hydroxyl radicals, significantly improving its capacity to remove pollutants that are resistant to conventional treatment methods. Ozone-based AOPs are commonly applied to eliminate contaminants like haloacetic acids, microcystins, and other hazardous byproducts from disinfection processes, as highlighted by the growing interest in treating emerging contaminants.	[41,47,51]
	Electro-Fenton and Fenton-Based AOPs	Electro-Fenton is a modified version of the Fenton reaction: a degradation mechanism based on the generation of hydroxyl radicals by the use of hydrogen peroxide with iron salts. The Fenton process is convenient for treating wastewater with high levels of organic pollutants. The conventional Fenton process has several limitations as it produces iron sludge, which has stimulated research on modified Fenton processes (photo-Fenton, electro-Fenton, etc.) to alleviate these drawbacks while enhancing the efficiency of pollutant removal. The photo-Fenton process produces chemical sludge that must be treated, which increases the costs for treatment plants.	[47,49,50]

2.2. Generation of Drinking Water Treatment Sludge

DWTS is an unavoidable byproduct of the wide range of processes required to produce safe drinking water (it is produced during the sedimentation and filtration stages). This sludge mainly composed of residual products of coagulation, flocculation, sedimentation and filtration (Figure 2) processes has complexity in its characteristics, both in volume as well as composition. DWTS is an essential environmental problem as water treatment facilities must cope with high demands for clean water (especially in rapidly urbanizing regions) that entail the handling of a large volume of DWTS [11,52].

Urban sprawl in many parts of the world, including Morocco, has resulted in more areas producing DWTS. Conventional water treatment methods tend to compound this increase using coagulants such as alum and iron salts. These coagulants play a major role in the chemical composition of the sludge (70% of the waste produced by DWTPs), containing elevated concentrations of metals, organic matter, and several other pollutants [53–55]. DWTS composition is largely dynamic, and it can vary quite widely depending on the quality of the source water (freshwater region, saline–alkaline region), types of chemicals used in treatment (flocculants and coagulants nature), and specific treatment processes applied at a facility. The organic content of sludge from regions with high levels of natural organic matter (NOM) in the source water set a limit on disposal and reuse opportunities. Seasonal differences, by their nature, are also to be expected as changes of temperature can

impact on the effectiveness of coagulation and the characteristics of the waste sludge [56–58]. One of the worst disposal methods used by DWTS has been landfilling or even illegal direct discharge into water bodies. Such practices, nevertheless, have been increasingly considered as not being unsustainable due to their environmental-associated risks, such as the leaching of hazardous compounds into groundwater and metal soil accumulation in the long term [5,59,60]. Thus, there is an increasing emphasis on the sustainability of DWTS management practices, including resource recovery and beneficial reuse [5,61]. DWTS as a soil amendment or fertilizer in agriculture to utilize its nutrient content has also been explored by researchers over the years. Nevertheless, the presence of hazardous constituents (heavy metals) is liable for environmental pollution if not competently controlled and maintained. Research has also observed that while DWTS can enhance soil properties, improper handling and application may be hazardous [62,63].

Since the concentration of metals in DWTS is low and it has a porous structure, the sludge can also be used for the adsorption of pollutants and heavy metals for wastewater treatment [58].

2.3. Characteristics of Drinking Water Treatment Sludge

2.3.1. Physicochemical Characteristics of DWTS

Coagulants such as alum [$Al_2(SO_4)_3$ $14H_2O$], $FeCl_3$, and $Fe_2(SO_4)_3$ are commonly used to remove particulate and dissolved substances from water sources during the drinking water production process. The resulting waste product, known as water treatment residuals (WTR), contains precipitated aluminum and iron oxyhydroxides, which have a strong affinity for anionic species [60]. Drinking water treatment relies on significant proportions of aluminum and iron (the most essential types of coagulants used) [61]. The basic elements of the sludge formed include organic matter and soil separators in addition to Al_2O_3 and Fe_2O_3 (amounts varying according to the amount used) [64]. In this axis, we will focus only on alum sludge, which is formed from aluminum sulphate ($Al_2(SO_4)_3$, $14H_2O$), which is considered the most used coagulant in water treatment plants. Organic and suspended inorganic materials are considered sludge components in addition to various microbes, secondary coagulation products and chemicals [11,65]. Aluminum (the main element in alum sludge) varies in percentage from one station to another according to the quantities of coagulants added in the water treatment process [66]. Source water plays an important role in the quality and purity of alum sludge [13,65]. Climate and seasonal changes, treatment processes, and chemical use cause sludge properties to vary from one plant to another depending on the location [67]. Table 2 shows the physical and chemical properties of DWTS, summarized from the literature and compared to relevant standards.

Table 2. Physicochemical characteristics of DWTS reported in the literature and reference limit values.

Parameter	Unit	Basis/Matrix	Range	References
(a) Solid phase (sludge)				
General properties				
pH		Suspension	4.28–8.4 (Al-based) 3.9–7 (Fe-based)	[11,53,60,65,68–72]
pH_{PZC}		Solid	5.49–6.9	[68,73]
EC	dS/m	Suspension	0.04–6.9	[11,60,68–70,74–79]
CEC	cmol(+)/kg	Solid	6.2–66.76	[11,68–70,76,78]

Table 2. *Cont.*

Parameter	Unit	Basis/Matrix	Range	References
$CaCO_3$	%	Solid	1.87–14.8	[75,78]
Major elements				
Total Ca	g/kg	Solid	0.081–129.8 (Al/Fe-based) 352.3 (Ca-based)	[11,68,69,71]
Total Al		Solid	12.8–174.6 (Al-Based) 1.34–9.8 (Fe-based)	[11,14,53,68,69,71–74,80]
Total Fe		Solid	3.34–90 (Al-based) 170–328 (Fe-based)	[11,53,60,68,69,71,73,74,80–82]
Total Mg		Solid	0.083–49.16	[11,68,69,71,81]
Total Mn		Solid	0.024–2.99	[11,60,68,69,81]
Total K		Solid	0.004–20.06	[60,68,77,81,82]
Total Na	mg/kg	Solid	36–1600	[60,68,81]
Nutrients, carbon and anions				
Total N	g/kg	Solid	0.54–18.4	[11,53,68–71,73,74,78]
NH_4^+-N		Solid	0.022–0.263	[11,60,69,70,78]
NO_3^--N		Solid	0.0035–0.298	[11,60,69,70,78]
Total P		Solid	0.3–4.36	[11,53,68,71,72,74]
Total C		Solid	12.7–423.8	[11,53,68,71,73]
Organic C		Solid	17–149	[24,70,76,78]
Organic matter		Solid	37.5–356	[11,68,69,71,75]
Chloride	mg/kg	Solid	146–16,410	[81,83]
Sulfate		Solid	35–9730	[81,83]
Trace elements				
Total B	mg/kg	Solid	69.6	[68,69]
Total Zn		Solid	14.37–167.1	[11,14,24,69,77,81]
Total Ni		Solid	5.3–64	[11,60,68,69,77,81]
Total Pb		Solid	1.99–121	[11,24,68,73,77,81]
Total Cr		Solid	14.3–81.1	[11,14,24,73,77,81]
Total Cd		Solid	0–4.5	[80,81]
Total Hg		Solid	0.02–8.19	[11,24,68,77,81]
Total As		Solid	8.01–34	[24,68,77,80]
Total Mo		Solid	<0.1–3.7	[60,68,69]
Total Se		Solid	0.067–1.5	[68,77]
(b) Liquid phase				
Turbidity	NTU	Supernatant	21.7–26.7	[84]
Conductivity (dS/m)	dS/m	Supernatant	2.9–2.99	[84]
Al	mg/L	Supernatant	1.4	[84]
Sulfate		Supernatant	1035–1303	[84]
		Sludge water	83.1	[85]
Chloride		Supernatant	568–585	[84]
		Sludge water	240	[85]

Table 2. *Cont.*

Parameter	Unit	Basis/Matrix	Range	References
Ca	mg/L	Sludge water	36.2	[85]
		Water extract	60–375	[78]
Mg		Sludge water	12.3	[85]
		Water extract	4.7–7.65	[78]
K		Sludge water	10.3	[85]
Na		Sludge water	54.3	[85]
Silicate		Supernatant	7.94–8.07	[84]
Si		Water sludge	1.76	[85]
B		Supernatant	0.24–0.32	[84]

The pH values of the Al-DWTS are between 4.28 and 8, corresponding to acidic to slightly alkaline and neutral conditions [11,68]. A pH range is common in sludge, but if used as a soil amendment, it can affect soil health in significant ways. Most crops prefer a near-neutral pH, the availability of nutrients and microbial activity can be affected [74,86]. Adding the sludge to the soil is an effective use of the DWTS method, and it also needs to be complemented with proper pH adjustment [68,75]. The electrical conductivity ranges between 0.04 and 6.9 dS/m, which indicates the salinity of alum sludge, which can be an obstacle for plants in agricultural use; however, most values are less than 4 dS/m [11], but some sludges exceed this value [68]. Continuous monitoring is necessary to avoid negative effects on the soil and plant growth [60,74]. The CEC values of DWTS range between 6.2 and 66.76 cmol(+)/kg, and the reported values differ significantly among sludges [68]. Seventeen water treatment residuals (WTRs) showed CEC values of 13.6–56.5 cmol/kg, generally higher than the typical range of soils (3.5–35.6 cmol/kg), which indicates that these materials may retain and supply cationic nutrients for agricultural applications [70]. CEC plays a vital role in enhancing soil structure (effect on nutrient retention). The factor that gives the sludge acidity is the calcium carbonate equivalent (which indicates the capacity to neutralize acidity), which ranges from 1.87% to 14.8% [75,78].

The calcium content in solid DWTS is between 0.081 and 129.8 g/kg [11,69], whilst the total Al content, for Al-based sludge, is between 12.8 and 174.6 g/kg (calcium has a positive impact on the soil; unlike soluble or available Al, it is far too high). Possible toxicity must be monitored to reduce adverse effects [87–89]. Nutrient levels, including NH_4^+-N (0.022–0.263 g/kg), NO_3^--N (0.0035–0.298 g/kg), and Total P (0.3–4.36 g/kg), vary widely. These nutrients are beneficial for soil fertility but should be balanced to avoid excesses that could lead to nutrient runoff and water pollution. To reduce environmental risks, nutrients must be managed properly [11,60,70,72]. Heavy metals are present in varying concentrations (total zinc ranges between 14.37 and 167.1 mg/kg, total lead between 1.99 and 121 mg/kg, nickel up to 64 mg/kg, and chromium up to 81.1 mg/kg). As for cadmium and total mercury, their concentrations reach 4.5 mg/kg and 8.19 mg/kg, respectively (for solid sludge). It is necessary to strictly monitor the use of these metals, as they are among the elements that most affect plants and pollute the environment [24,81]. For organic matter, it ranges from 37.5 to 356 g/kg (a major factor in soil fertility and contributes to improving its structure). The presence of both organic carbon (17–149 g/kg) and other trace elements (such as arsenic, which reaches a concentration of 8.01–34 mg/kg; molybdenum reaches 3.7 mg/kg and selenium reaches 0.067–1.5 mg/kg) can affect soil quality and potential toxicity, so it needs careful consideration [24,60,68,77,80].

2.3.2. Characterization Techniques of DWTS

To support this review of DWTS, it was characterized using techniques that allow for us to determine its properties, particularly in the solid state, so that these techniques can help assess the suitability of the sludge for applications that rely on the solid state of materials, such as adsorption or as a soil substitute. At 3000× magnification, the sludge revealed an amorphous structure (absence of crystalline phases), confirming the absence of any morphologies associated with the crystalline $Al(OH)_3$ phases. SEM consistently revealed amorphous and irregular sludge particles (it is composed mainly of silica, aluminum and iron oxides), supporting the suitability of this material for adsorption applications [90–92]. During the coagulation and flocculation process, abundant surface pores are formed on the sludge, resulting in irregular shapes, which give a high capacity for adsorption of organic matter and heavy metals [60,68,73]. Through SEM, combined with XRD and XRF, the main components of the sludge are quartz (SiO_2), Al_2O_3 and Fe_2O_3 (depending on the coagulant solution used), which shows the potential of this material for multiple applications such as soil amendment, adsorption and building materials, due to its unique properties [52,68]. Abo El-Enein et al. [22] found, through SEM images, that thermal treatment contributes to the change of the microstructure of DWTS, with changes in shape with increasing temperature. At 100 °C, a mesoporous structure was observed, which increases the surface area for higher adsorption capacity. However, the intermediate range of application must be determined when increasing the temperature during treatment. Increasing the temperature up to 700 °C, it led to a reduction in pores and narrowing of the structure and thus reduced the adsorption capacity. The rapid transformation, microstructure, formation, and disappearance of albite phases are the main reasons for thermal treatment to improve sludge properties for specific applications [22].

In a study conducted by Hovsepyan et al. [24] on Al-WTR_S (aluminum water treatment residues), irregular particles of different sizes (heterogeneous mixture) were observed, despite its advanced age and different aging times, the alum sludge retains its amorphous structure. Cylindrical shapes and medium-sized pores were observed in the samples through SEM, indicating that the sludge retains its morphological characteristics [83].

X-ray diffraction (XRD) was applied to determine the mineralogy and crystal structure of DWTS, and it was shown that it is mainly composed of quartz, kaolinite, muscovite, and other mineral phases. XRD analysis of the sludge dried at 105 °C for 2 h showed a significant presence of SiO_2, and both kaolinite and muscovite were detected, indicating that the sludge is kaolinite–muscovite in nature, and other mineral phases included dolomite and talc [93]. XRD further supported those results, and it was observed that the reason for the effect of heat treatment on the structure of the sludge was due to the change in its mineral structure, as proven by Abo-El-Enein et al. [22]. When they exposed the sludge to a temperature below 500 °C, the SiO_2 and illite phases were constantly present, while when the temperature reached 500 °C, the albite phase appeared. Quartz and illite are the most essential minerals that give sludge the ability to absorb heavy metals due to their structural and chemical properties, through the exchange of ions and the creation of inner-sphere complexes through $Si\text{-}O^-$ and $Al\text{-}O^-$ groups at their boundaries. Illite, a 2:1 clay mineral, is effective at adsorbing heavy metals [22].

ANYAKORA et al. [94] highlighted the significant occurrence of silica and alumina in DWTS, which constitutes over 58% of its weight. Such a composition is largely attributed to the aluminum sulfate (alum) used in the coagulation treatment, in combination with iron oxide, responsible for the rust-like pigmentation [94]. The mineral nature of DWTS also enables it to be used in building materials, due to its ability to retain its crystalline nature despite aging times. Fresh alum sludge showed an amorphous nature with no crystalline peaks associated with aluminum in XRD patterns [83]. A major peak due to

crystalline silicon oxide (SiO_2), however, was always present. The result indicates that the sludge is stable with time, with an amorphous nature. XRD analysis by Wu et al. [95] provided additional verification of silicon dioxide as the predominant inorganic constituent (Figure 3). The presence of crystalline phases of Al_2O_3 and Fe_3O_4 was also revealed by low-intensity peaks, indicating that these phases are minor constituents [95].

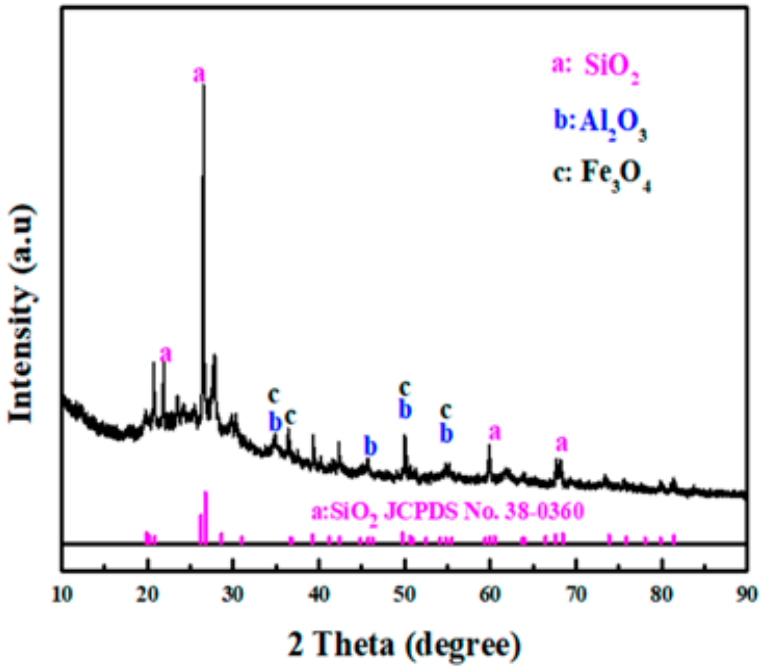


Figure 3. X-ray diffraction pattern of DWTS, reproduced from [95], under CC BY 4.0 license.

Using FTIR, in the same manner, Ahmad et al. [91] observed a broad band at 3519 cm^{-1} due to O-H vibrations and a band at 1642 cm^{-1} due to bending vibrations of water molecules. Bands at 1092 cm^{-1}, 857 cm^{-1} and 782 cm^{-1} were due to stretching and bending vibrations of quartz Si-O-Si and O-Si-O were observed at 470 cm^{-1}. These findings also affirm the relevance of silicates and hydroxides in the chemical and structural makeup of DWTS. The stability of functional groups in DWTS, even under ageing, has been proved by Yang et al. [83]. Through ATR-FTIR, they found stable peaks at 3427 cm^{-1} (OH o for all sludge samples regardless of the ageing time). This result demonstrates that the functional groups, including hydroxyl groups and humic substances, were stable, thereby establishing the long-term viability of DWTS in adsorption and similar processes. The chemical composition of DWTS, as indicated by FTIR analysis, offers an important basis for its prospective applications. The availability of hydroxyl (-OH) and silicate functional groups in the spectra is very important for adsorption processes. Hydroxyl functional groups promote ligand exchange reactions that are vital for the adsorption of phosphorus and heavy metals, as indicated by YUSUFF et al. [23] and Yang et al. [83]. Silicates provide the structural stability of DWTS, thus improving its efficiency in practical use. The comparison of FTIR results from various studies highlights the consistency and applicability of DWTS properties. YUSUFF et al. [23] pointed to the contribution of aluminum hydroxides and silicates to adsorption; Ahmad et al. [96] stressed the existence of quartz as an important constituent for the structural stability [96]. Yang et al. [83]. demonstrated the stability of functional groups during ageing, reaffirming the material's long-term applicability.

TEM analysis also gives a close look at DWTS microstructure and composition. Elmontassir et al. [93] noted a heterogeneous mixture of particles with non-uniform shapes such as sheets and granules made of minerals with rounded shapes. Elemental analysis

proved the existence of Al, Si, Fe, Cu, and K, which mirrors the use of alum and impurities from treated water. Such a varied microstructure and composition improve DWTS's functional properties [93].

Thermogravimetric analysis (TGA) has been broadly utilized in investigating the thermal decomposition of DWTS. Thermal degradation of DWTS, according to YUSUFF et al. [23], takes two stages. In the first stage, seen at temperatures below 150 °C, is the thermodesorption of physically adsorbed water molecules. In stage 2, between 150 and 550 °C, is represented by the decomposition of aluminum hydroxide and metal hydroxides such as iron and potassium, producing respective oxides and water. The thermal behavior is indicative of chemical transformations in DWTS under thermal conditions, and it, therefore, is a matter of concern for its reuse in processes such as adsorbents and in construction materials. Soleha et al. [97] have stated that in untreated DWTS, 12.5% overall loss in weight occurs, but in 300 °C thermally processed sludge, a reduced loss of 9.1% occurs. Initial loss in weight occurs with free water evaporation at about 60–80 °C. There is a secondary loss in weight at 257 °C, with loss of water in hydroxides and burning of organic matter following it. All such observations have been corroborated with supporting studies, including studies in which organic compound desorption and decomposition in carbonylated compounds in sludge have been discussed. The final appreciable loss in weight, at 480–550 °C, reflects loss in structure water in kaolinite and in other minerals [98,99]. But in 800 °C thermally processed alum sludge, no significant weight loss occurs, proving its high-temperature stability [97]. According to Sousa et al. [100], the total mass loss range of DWTR was between 28.6 and 45.6% after activation and regeneration processes (Figure 4). Around 750 °C, the DWTR samples showed the largest mass loss, which could be related to the degradation of $CaCO_3$. The TGA analysis reveals necessary transformations in DWTS during thermal processing, with each degradation stage defined through individual chemical transformations. All such processes have an impact on the chemical character and structure of the sludge and its reusability, for instance, thermal processing decomposition of kaolinite, with increased pollutant adsorption capacity and surface area of material [97].

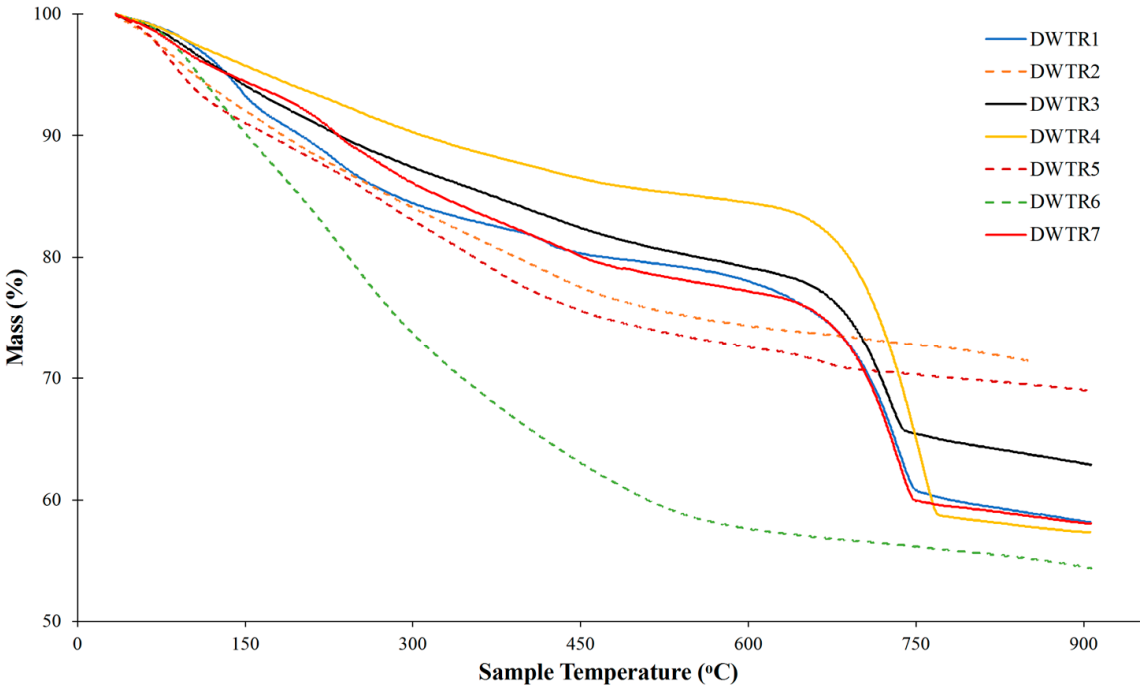


Figure 4. TGA of the DWTR, reproduced with permission from [100], under CC BY 4.0 license.

The BET (Brunauer–Emmett–Teller) surface area of alum sludge varied with ageing times, with values for freshly prepared, six-month-old, and 12-month-old and 18-month-old samples 49.03 m^2/g, 62.33 m^2/g, 54.60 m^2/g and 53.54 m^2/g, respectively; not surprisingly, even with a significant rise in the six-month-old samples' surface area, ageing-related transformations in samples could not be assured, but between samples, variation could be noticed [83]. Thermal treatment significantly controls the porosity and surface area of alum sludge [97]. Soleha et al. [97] have reported that the specific surface area in raw alum sludge decreased appreciably when processed at 800 °C. Adsorption pores increased marginally with 300 °C thermal processing but leveled off to values similar to those of raw sludge at 800 °C thermal processing. Pore diameters, nevertheless, increased with temperature, with an intensification of the mesoporous character of alum sludge, with diameters between 2 and 50 nm [97]. Observations present susceptibility of adsorption behavior in sludge towards thermal transformations. Table 3 shows the chemical oxide composition of DWTS summarized from the literature.

Table 3. Chemical oxide composition (wt.% of dry solids) of dried Al-DWTS determined by XRF.

Oxide	Weight, %	References
SiO_2	33.08–52.78	[22,93,96,101,102]
Al_2O_3	12.1–51.1	[22,93,96,101–103]
Fe_2O_3	3.07–12.4	[22,93,101]
CaO	0.5–9.79	[22,93,96,101–103]
MgO	0.52–4.88	[22,93,96,101–103]
SO_3	0.08–3.79	[22,93,102,103]
K_2O	0.49–4.2	[22,93,96,101–103]
TiO_2	0.36–2.2 [1]	[93,96,101,102]
MnO	0.08–1.07	[93,96,101–103]
P_2O_5	0.17–0.63	[96,102,103]
Na_2O	0–1.35	[22,93,96,102,103]
SrO	0.025	[102]
ZnO	0.01	[96]
Loss on ignition (L.O.I)	4.45–28.1	[22,102]

[1] The origin of minor oxides such as TiO_2 was not specified in the cited studies, and their potential risks, including TiO_2 nanotoxicity, should be assessed before DWTS reuse.

2.4. Challenges and Limitations

The management of DWTS is characterized by many complications that hinder effective and efficient processing. One of its key concerns involves its chemical composition, which in many cases contains toxic compounds such as heavy metals (arsenic, lead, and cadmium), pathogen microorganisms, and trace organic matter. These toxic compounds make its direct use in application challenging through degradation in soil, agricultural unsafety, and groundwater contamination in cases of poor treatment and stabilization [22,104]. DWTS tends to have high moisture content, which makes its processing challenging, increases transportation expenses and makes drying processes costly [59,105]. High moisture content is a key challenge that renders its disposal and reuse not economical, save for in cases where sophisticated dewatering and drying processes are utilized. In addition, DWTS's uniformity is a challenge, as its composition varies with source water purity, chemicals added during processing, and operational factors water processing. Its lack of uniformity in its behavior, therefore, makes its reuse protocols and suitability for use in a specific purpose, such as in adsorption and amendment, challenging [11].

In most cases, effective and transparent legislation guiding its disposal and reuse in many developing nations does not exist, and even when it does, its provisions tend not to be uniform, leading to inconsistent management and hindering efficient reuse. There is, in

addition, a technological barrier to its integration in a whole range of waste management programs. The inclusion of sewage sludge can have a bearing in raising aluminum and coagulant concentrations, and subsequently, effluent standards can be broken and reuse options reduced. Lacks in infrastructure for its reuse and re-treatment, specifically in relation to advanced contaminant removal and stabilization, make its disposal in a landfill manner even a problem; most times, it ends in disposal in a landfill manner, and this encourages extended leaching of toxic compounds in the environment [106].

The problem raises a critical issue for new and renewable approaches in effectively combining reuse with processes for its sludge treatment. Involvements in cost-effective and flexible technology for dewatering, contaminant extraction, and retrieval of useful resources, such as thermal processing, acid activation, and geopolymer techniques, have potential for safe and effective use in agricultural applications, such as agricultural adsorption and many additional processes. Overcoming such a problem is not only important in minimizing its impact on the environment but also in supporting a circular economy by converting its use into a valuable source [16,26]. This development opens doors for its reuse in agricultural use and adsorption, with considerable room for future development in a circular economy and for effective and safe reuse options.

3. Valorization of Sludge from Drinking Water Treatment Plants

3.1. Reuse of Sludge in Agriculture

3.1.1. Assessment of Alum Sludge Toxicity and Aluminum Removal

Alum, scientifically aluminum sulfate ($Al_2(SO_4)_3$), is regularly utilized in coagulation during potable water treatment for the purpose of getting rid of suspended matter, microorganisms, and other types of impurities. In reaction with water, a reaction takes place that releases aluminum ions (Al^{3+}), which become incorporated in the residual sludge, with a potential aluminum-by-weight concentration of even 39% after coagulation [107]. Recycling potable water sludge generated through potable water treatment, and specifically one utilizing alum, for agricultural use holds considerable potential for creating environmentally friendly disposal techniques and for improving soil fertility. Overcoming concerns about toxicity in alum sludge is imperative for developing its safe and beneficial use [15,62,108]. Having aluminum in potable water treatment sludge creates considerable concern, particularly with regard to its potential toxicity to flora and surrounding environments. Released in aquatic environments, aluminum has been proven to cause toxicity in aquatic life, and its presence in alum sludge raises concerns regarding its impact on agricultural activity, particularly in arable lands for planting crops. Aluminum presents a critical danger to aquatic life, and its toxicity is heightened in acid environments [87]. In aquatic environments, aluminum in its form of alum sludge can inhibit algal growth, disturb aquatic communities, and cause long-term ecological deterioration [88,89].

A multitude of studies have examined both long-term and immediate consequences of alum sludge on agricultural productivity and soil health. According to Skene et al. [109], even though alum sludge is not acutely toxic when used as a growth medium [109], its long-term effects in terms of aluminum concentrations, specifically in relation to soil health, reveal significant concerns. Sotero-Santos et al. [110] indicated that alum sludge affects the reproductive capacity of the aquatic organism Daphnia similis upon long-term exposure (as opposed to short-term exposure), suggesting a risk to water bodies that come into contact with this sludge; this risk must be taken into account in agricultural applications [110]. Contamination of soils with aluminum can hinder the availability of nutrients, disintegrate the structure of the soil, and inhibit root development in plants. Thus, it is imperative to understand and manage alum sludge toxicity to enable its safe use in agricultural production processes. In acid environments, aluminum in alum sludge can become mobilized in

the soil, enhancing its toxicity potential. Mobilization and bioavailability of aluminum in alum sludge depend on soil pH, with a drop in pH enhancing aluminum solubility and toxicity [11,70,111]. Mobilization and bioavailability of aluminum in acid environments make aluminum leaching in acid-sensitive environments a significant challenge in determining suitability for use of alum sludge in the amendment of soil, with aluminum toxicity in relation to crops and microorganisms in soil becoming a concern in acid environments [105].

3.1.2. Aluminum Removal from Alum Sludge

To mitigate toxicity with regard to agricultural use of alum sludge, numerous approaches have been proposed for aluminum extraction and/or aluminum neutralization. One of the most common techniques for aluminum extraction involves acid treatments, in which strong acids, including sulfuric acid, are utilized in processing alum sludge. According to studies, aluminum can effectively be recovered through such a mechanism, with studies reporting a 70% to 90% recovery in acid environments [11,112]. Solubilization of aluminum is involved in acid treatments, through which its subsequent extraction and recovery can occur from the sludge. Despite effectiveness in aluminum extraction, acid treatments have received criticism for concerns over potential environmental impact consequences of strong acid use, including acidification of both soil and aquatic environments [113]. As an alternative, the use of sodium and calcium hydroxides in alkaline processes has been proposed for aluminum extraction from alum sludge [105,114]. The maximum extraction rates of alum coagulant were 84.18% and 76.98% based on acid and alkaline methods, respectively [115]. Alkaline conditions can also influence the reduction of aluminum solubility by adding lime to aluminum-based sludge (raising the pH of soil to above 8), in addition to converting aluminum-bound phosphorus into calcium-bound phosphorus [116]. pH plays an important role in aluminum solubility; at high alkaline pH, aluminum is more readily absorbed by living organisms, whereas under neutral conditions, Al compounds are insoluble [117]. Therefore, it is important to control the pH when applying alum sludge to soil to avoid aluminum toxicity.

Advanced technologies, including ion exchange and membrane processes, have been examined for efficiency in aluminum extraction from alum sludge [118,119]. In these processes, selective ion exchange resins or membrane filtration methods are employed for the selective recovery of aluminum and aluminum separation from other components in the sludge [118,119]. Although they are very efficient and selective, concerns regarding their suitability for bulk agricultural application and economy remain, and therefore, ongoing research on these technologies is still necessary.

The latest technological advancement has witnessed new extraction processes of aluminum from alum sludge with potential outputs that are environmentally friendly and agriculturally valuable. Among them is the AquaCritox technology, which uses supercritical water oxidation [11]. In such a process, alum sludge is subjected to temperatures between 374 °C and 500 °C and high pressures in an environment rich in oxygen, as shown in Table 4. Under such a state, organic matter in the sludge is subjected to full oxidation, producing water, carbon dioxide, and aluminum hydroxide in the form of a precipitate. Afterward, aluminum hydroxide can then be recovered and possibly reused in water purification processes, offering a form of sustainable aluminum extraction and application in such water purification processes [11]. Table 4 summarizes the methods used to remove aluminum from alum sludge extracted from the literature.

Table 4. Methods used for aluminum removal from alum sludge.

Method	Description	Effectiveness	Sources
Acid treatment	Alum sludge is treated with sulfuric acid to dissolve aluminum. The aluminum can then be separated from the sludge.	Recovery rates of 70–90% depending on pH conditions (pH between 1.0–3.0).	[120]
	The WTR is acidified with sulfuric acid, and the insoluble $Al(OH)_3$ is dissolved in the form of diluted liquid alum	At pH = 2.67, the recovery efficiency of alum reached 84.18%.	[115]
	Acid washing (pH = 3) was used to remove aluminum from the sludge and apply it to the soil for agriculture	The aluminum content in the waste was reduced by up to 90%.	[59]
	The alum sludge was dried and mixed with distilled water at different concentrations of H_2SO_4. The highest percentage of aluminum recovery was obtained.	98% recovery was achieved after 1.35M of H_2SO_4 with 300g of sludge.	[121]
	Centrifuged PACl sludge leached with concentrated H_2SO_4; dry sludge/acid solution ratio 0.5–2%, pH 1.0–4.5, with varied stirring and settling times.	Maximum Al recovery ≈ 61% at pH 1.0; higher co-dissolution of Fe (18.2%) and Mn (42.1%).	[15]
Alkaline treatment	Alum sludge is treated with alkaline solutions (NaOH or $Ca(OH)_2$) to precipitate aluminum hydroxide, reducing its bioavailability.	High efficiency at pH ranges of 11.4–11.8 for sodium hydroxide and 11.2–11.6 for calcium hydroxide.	[114]
	NaOH is added to the WTR, and Al^{3+} is returned to the solution in the form of sodium aluminates.	at pH = 12, the recovery efficiency of alum reached 76.98%.	[115]
	Centrifuged PACl sludge leached with 2N/10N NaOH at pH 10.0–13.6 (2% dry sludge, 90 min stirring, 45 min settling).	Al recovery was 71% at pH 13.6; 87.4% at pH 13 with 0.5% sludge dosage.	[15]
Acid and alkaline extraction	Comparison of aluminum extract quality and aluminum recovery yields from different types of alum sludge between alkaline and acid extraction methods.	Nearly 90% recovery of aluminum in intact and pretreated AS.	[112]
Ion exchange	Aluminum ions are selectively exchanged with other ions using ion exchange materials, separating aluminum from the sludge.	High selectivity, efficient for aluminum recovery.	[118,119]
Membrane-based electrochemical process	Alum sludge is acidified to dissolve aluminum as Al^{3+}. Then, an electric field is applied across a cation exchange membrane, CEM, which selectively transports Al^{3+} ions according to ionic charge and separates them from other solids, organics, and other dissolved impurities.	Total aluminum recovery reached 66.74% at pH = 2, consisting of 16.61% solid $Al(OH)_3$ and 50.13% soluble aluminate species ($Al(OH)_4^-$).	[122]
	Uses an anion exchange membrane (AEM). Aluminum tends to precipitate in the cathode chamber instead of migrating efficiently, resulting in lower separation performance.	Total aluminum recovery reached 38.45% at pH = 2, consisting of 24.95% solid $Al(OH)_3$ and 13.50% soluble aluminum species.	
Supercritical water oxidation (AquaCritox process)	Alum sludge is heated to high temperatures (374–500 °C) and high pressures (221 bar) in the presence of oxygen, oxidizing organic matter and precipitating aluminum hydroxide.	Effective for complete oxidation of organic matter and aluminum recovery.	[11]

3.1.3. Positives and Negatives of Sludge Application in Agriculture

- Negatives of sludge use

The application of DWTS in agriculture holds potential for its use both as a source of nutrition and a soil improver, but extraction methodologies for aluminum often threaten healthy soil integrity and agricultural viability. For instance, acid processing is effective at removing aluminum through extraction, as demonstrated by experiments conducted by Panswad et al. [120], Vaezi et al. [123] and Boaventura et al. [15]. Nevertheless, acid produced during processing can alter soil pH, creating an environment with reduced microbial activity and reduced availability of nutrients. Solubilization of secondary metals including iron and manganese creates concerns about heavy metal build-up in the soil, capable of inhibiting plant growth and contaminating food chains through heightened toxicity [124]. Without proper pH controls and processing, produced sludge can cause additional detrimental consequences when added to agricultural lands [125]. Methods utilizing an environment with an alkalinization allow for increased aluminum extraction but produce specific consequences for healthy soil [126–128]. Byproducts produced through such processes have high alkalinization and, when incorporated into soil, can destroy native acid–base balance and cycling processes for nutrients [129]. Necessary nutrients such as phosphorus become immobilized under such processes, becoming less accessible to produce and creating reduced yields [100]. High-energy requirements of such processes, in addition to chemicals involved during processing, complicate concerns regarding its use in an environmentally friendly and economically feasible manner in agricultural settings. Ion exchange processes, present a specific mechanism for aluminum extraction but have its own range of complications [118,130]. The organic compounds and impurities present in sludge can foul ion exchange resins, causing a drop in efficiency and necessitating constant regeneration. Chemicals utilized in resin regeneration processes have a tendency to leave residues in processed sludge, capable of accumulating in the long run in the soil and having a detrimental impact on soil properties and long-term agricultural productivity. All these limitations hinder ion exchange processes for agricultural use at a larger level. Membrane-based membrane separation or electrochemical processes have the potential to extract aluminum from sludge and enrich both organic and inorganic impurities [122]. Concentrating such impurities could introduce toxicity to both plants and microorganisms in the soil when the sludge is added to it as an amendment. Additionally, high operational expenses and high energy requirements involved in membrane processes make them less feasible for widespread agricultural use, especially in regions with poor financial and technical capabilities.

Thermal treatment processes have proven effective in stabilizing pollutants and minimizing volumes of sludge, according to Boaventura et al. [15]. However, such processes often cause degradation of useful organic matter in the sludge, effectively reducing its value for use in a soil amendment role. In addition, high-temperature thermal processes produce greenhouse gases and other emissions that present significant environmental concerns; therefore, such technology is considered less sustainable for agricultural use. Supercritical water oxidation (SCWO), represented by AquaCritox [11], is a new technology for stabilizing sludge. In addition to its many beneficial factors, SCWO use is restricted by its high operational expense and necessity for specific infrastructure. SCWO can, in addition, modify the chemical makeup of the sludge, and such a change reduces its value for use in a role as a soil amendment and restricts its availability for use in an agricultural role.

- Positives of sludge use

Application of DWTS as a soil amendment provides effective benefits for nutrient supply and soil amelioration; it is also a good reservoir of major and essential nutrients like

phosphorus, potassium, calcium, magnesium and certain trace elements such as zinc, copper and iron Fe besides the organic C, N and P [131,132]. In addition to aluminum and iron hydroxides, DWTS contains organic carbon, nitrogen, and phosphorus [11]. However, the nutrient contents reported in Table 2 are total concentrations (e.g., total P of 0.3–4.36 g/kg and total K of 0.004–20.06 g/kg), which do not indicate the fraction available for plant uptake. Phosphorus availability in DWTS is generally low, because phosphorus is strongly retained by aluminum hydroxides [53,72,133]. In a study of 17 water treatment residuals, Mehlich-III-extractable P ranged from 1.6 to 54.4 mg/kg, and several residuals were considered deficient in available P due to its fixation by Al–OH groups; tomatoes grown on these residuals showed inadequate tissue P concentrations [70]. Potassium is an essential nutrient involved in photosynthesis, water regulation, and disease resistance in plants [134]. However, the potassium content of DWTS is low and variable: a DWTS used as a fertilizer contained only 0.18–0.21% K, compared with 1.7–1.9% P [77], and Mehlich-III-extractable K in water treatment residuals (19–278 mg/kg, median 109 mg/kg) was slightly below the level considered adequate for soils (125 mg/kg) [70]. Therefore, DWTS may contribute some nutrients when applied to soils, but they cannot replace mineral fertilizers, particularly phosphorus fertilizers, and supplementary fertilization is required [70]. The effect of soil amendment was also noticed in the changes in soil physical properties. This moisture retention is the presence of organic matter in sludge that helps to improve soil aggregation properties and to decrease bulk density [125]. Better soil structure will improve air and water permeability and root penetration needed for normal plant growth. Moreover, sludge will increase the water holding capacity (WHC) of soil, which is necessary where the region faces drought susceptibility [59,135].

The presence of some elements in high concentrations, such as heavy metals, may affect soil health and plant growth. These elements must be fully monitored, and their concentrations must be kept within the permissible limits for use, to avoid environmental impacts. As benefits to the application in terms of nutrient release from WTS application have to be weighed against soil and water, sludge applications need to be controlled strictly [124,136].

More understanding of the use of DWTS in diverse agricultural contexts has been provided through several case studies and practical applications. A study to diminish nutrient overflow from lands getting cleaned poultry muck confirmed that the amorphous aluminum content of sludge can reduce phosphorus runoff in plots treated, generating an enhanced capacity for binding phosphorus [78], and thus a possible mitigant for agricultural nutrient runoff. In Australia, DWTS has been used for the remediation of heavy metal-contaminated soils (Pb and Cd). According to their research, this application decreased the bioavailability of these metals and reduced the risk of metal accumulation in crops, and thus in the food [11]. Studies have demonstrated the effectiveness of sludge in agricultural and environmental applications and the potential for its use; however, the bioavailability of minerals in the soil and the accumulation of trace elements must be studied in order to assess the effectiveness and safety of sludge in repeated applications [137,138]. An illustration is offered by the study of Novak et al. [139] using DWTS, where changes in soil composition were examined; specifically, they incubated Norfolk sand soil with 60 g/kg of sludge for 60 days. Soil analysis results showed an increase in certain elements, such as organic carbon, manganese, sodium, and sulfur; conversely, a decrease was observed in the concentrations of both soluble aluminum and iron. This study highlights the importance of monitoring these byproducts when used on agricultural land, despite their role as soil amendments.

3.2. Reuse of Sludge for Adsorption

3.2.1. As a CO_2 Adsorbent

The efficiency of DWTS as a CO_2 adsorbent is enhanced by several key features that it possesses [23]. Its large surface area and porosity are among its main characteristics. DWTS consists of elements that enhance the adsorption of carbon dioxide, such as iron and aluminum oxides (abundant constituents) [68,95,100]. The surface area of the sludge and the large porosity contribute to the adsorption of CO_2 with a greater capacity [23] and for hydrogen sulfide [140]. Research confirms that the adsorption capacity of DWTS is affected by the functional group on its surface. Some factors affect the adsorption capacity, such as temperature, sludge dose, initial concentration of CO_2, and flow rate [141]. These conditions must be taken into account to make better use of the sludge in the adsorption process [23]. These functional groups, which include carboxyl and hydroxyl groups, can interact electrostatically and form hydrogen bonds with CO_2 molecules. Other methods improve the adsorption efficiency (pretreatment techniques enhance the adsorption capacity of sludge); for example, chemical modification introduces new functional groups that interact better with CO_2, and thermal treatment improves the pore size distribution and surface functions of sludge and removes organic impurities (creating more adsorption sites) [142]. It should be considered how chemical modifications involving new functional groups affect the adsorption capacity and efficiency of DWTS for CO_2 [23].

The performance of DWTS as a CO_2 adsorbent is improved by the presence of multiple important features. Its large surface area and porosity are two of its main characteristics [26,104]. To increase the adsorption capacity of CO_2, the absorbent material must have a large surface area, which is what characterizes the sludge resulting from a drinking water treatment plant [143].

In physical adsorption, a larger number of pores and a higher specific surface area provide more sites that can be occupied by CO_2 molecules, which generally increases the adsorption capacity [144,145]. The kinetic diameter of the CO_2 molecule is approximately 0.33 nm [146,147]; pores wider than this value are therefore accessible to CO_2, but accessibility alone does not ensure efficient adsorption. In porous carbons, CO_2 uptake has been mainly attributed to narrow micropores, close to the size of the molecule, whereas larger pores contribute less to adsorption at low pressure [146,147]. Consequently, pores larger than 0.33 nm do not all perform equally well, and the adsorption capacity also depends on the pore size distribution, the surface chemistry of the adsorbent, and the operating conditions, such as temperature and pressure [144,145]. It should be noted that these findings were mainly obtained for carbon-based and other engineered porous materials; for DWTS, experimental evidence on CO_2 adsorption remains limited [23], and the relationship between their pore structure and CO_2 uptake still needs to be established. For chemical adsorption, the functional group located above DWTS makes the binding more permanent due to the presence of the groups that contribute to capturing carbon with greater capacity and ability compared to other absorbent materials. And the spontaneity, as well as the feasibility of CO_2 capture, can be evaluated by the Gibbs free energy change associated with each adsorption. The main factor in changing the effectiveness and absorption capacity is temperature, but the effect remains large [144,145].

3.2.2. As a Heavy Metal Adsorbent

Sludge from drinking water treatment plants (DWTS) has shown promise as an adsorbent material for heavy metals, offering a long-term solution to the problems of sludge disposal and water contamination. The main constituents of this material are metal oxides, such as iron and aluminum, which are very good at adsorbing metal ions [22]. The highest capabilities of DWTS, fired at 500 °C, for the adsorption of lead (Pb), cadmium (Cd), and

nickel (Ni) at pH 5.5 were shown by Abo-El-Enein et al. [22] to be 10 mg/g for Pb (II), 9.1 mg/g for Cd (II), and 7.8 mg/g for Ni (II) (Table 5). DWTS can be used in other research as an adsorbent for heavy metals (especially in removing metals from wastewater), also by mixing it with other materials that allow for increasing the adsorption capacity due to its porosity. Du et al. [25] investigated a granular sludge–clay (GSC) composite adsorbent that enhanced the removal of Cd (II), Cu (II), and Zn (II). The study found that at a mass ratio of 1:2, GSC improved the sludge's adsorption efficiency while decreasing issues like caking and aluminum leaching. The results showed that GSC could adsorb up to 1.53 mg/g of Cd (II), 2.76 mg/g of Cu (II), and 1.23 mg/g of Zn (II) (Table 5). The most effective elimination was Cu (II) [25].

Research shows the ability of DWTS to adsorb metals. The adsorption capacity of molybdenum was increased by heat treatment and acid activation, which provided additional sites for adsorption (due to the sludge surface area and porosity) [26]. The pH value is essential for the adsorption of heavy metals in addition to the concentrations of the latter. Research has shown that the adsorption of Cd (II), Cu (II), and Zn (II) is greater at pH values of 4, 5, and 5, respectively. It can be concluded that the concentration of metals and pH levels have a significant effect on this issue [25,148]. The mixing of sludge and clay also leads to the emergence of more widespread and active sites on the sludge surface, resulting in enhanced GSC performance [25]. It appears that Cu (II) is absorbed more easily and more readily than Zn (II) and Cd (II) due to its increased charge density and its smaller ionic radius. This competition of multiple metal ions for the absorption sites, clearly and multiple ligands present in many applications, makes us understand the situation more clearly and simply. Cu (II) shows, thanks to the formation of stronger bonds at the active sites, a remarkable and different adsorption [25].

These findings suggest that DWTS has the potential for selective adsorption, particularly in systems with multi-metal contamination. Mercury (Hg), a highly toxic heavy metal, can also be effectively removed by DWTS. Hovsepyan et al. [24] demonstrated that it increases the adsorption of Hg(II) ions because of its high iron concentration. The importance of DWTS is also shown in its ability to adsorb mercury and iron from polluted water, preventing pollution from industrial sources [24]. The majority of industrial wastewater contains lead, which is also a metal that sludge deals with effectively during the adsorption process, strongly adhering to the sludge matrix. According to Almeida et al. [148] and Ghorpade et al. [149], hydroxyl groups are essential to the process of surface complexation (Figure 5), which is how DWTS adsorbs Pb (II) ions. Additionally, the study found that at alkaline pH values, adsorption increased, encouraging the development of lead hydroxides that bind to the aluminosilicates in the sludge [69]. Arsenic (As) is another dangerous element that DWTS can eliminate. Makris et al. [80] demonstrated that alum and iron-rich water treatment residuals were effective at adsorbing As (V) ions from polluted water. Because this sludge undergoes surface complexation, which occurs particularly at near-neutral pH values, it is an ideal material for treating arsenic-contaminated streams [150]. In a similar vein, DWTS efficiently removes selenium (Se), a hazardous element in high concentrations. Ippolito et al. [69] claim that surface complexation and electrostatic interactions with the Al hydroxides present in DWTS are the mechanisms (Figure 5) via which Se (IV) adsorption occurs. This was especially effective at lower pH levels, indicating that selenium adsorption efficiency is influenced by pH. DWTS is an effective technology for eliminating Cr, particularly in its hexavalent form, Cr (VI). Zhou et al. [16] showed that ions are converted to Cr (III) first, and then they adsorb onto the DWTS surface. In this study, Cr(VI) was mainly adsorbed onto the positively charged Al hydroxide surfaces, with maximum removal at pH 3–4, whereas adsorption of Cr(III) was higher and reached 100% between pH 3 and 6 [16]. Similarly, Ngatenah et al. [106] investigated Cu adsorption by GWTPS (groundwater

treatment plant sludge) and discovered that, using a Langmuir isotherm model, Cu (II) ions were successfully eliminated by monolayer adsorption. The adsorption capability of DWTS is further improved by modifications such as acid and heat treatments. Ocinski et al. [151] and Lian et al. [26] showed that the adsorptive capacity for Mo (VI) and As (V) was greatly enhanced by thermally treated and acid-activated sludge. These treatments increase the number of accessible binding sites by creating a more porous structure and increasing the surface area of the sludge. Similar conclusions were reached by Sharma et al. [104], who found that acid-activated sludge enhanced the removal of arsenic from contaminated water, offering a practical method of treating arsenic-containing wastewater. Studies on the use of geopolymers as an additional modification have demonstrated potential for increasing the adsorption efficiency of metals including iron, manganese, and arsenic [104]. Figure 5 shows the mechanisms involved in heavy metal adsorption by DWTS.

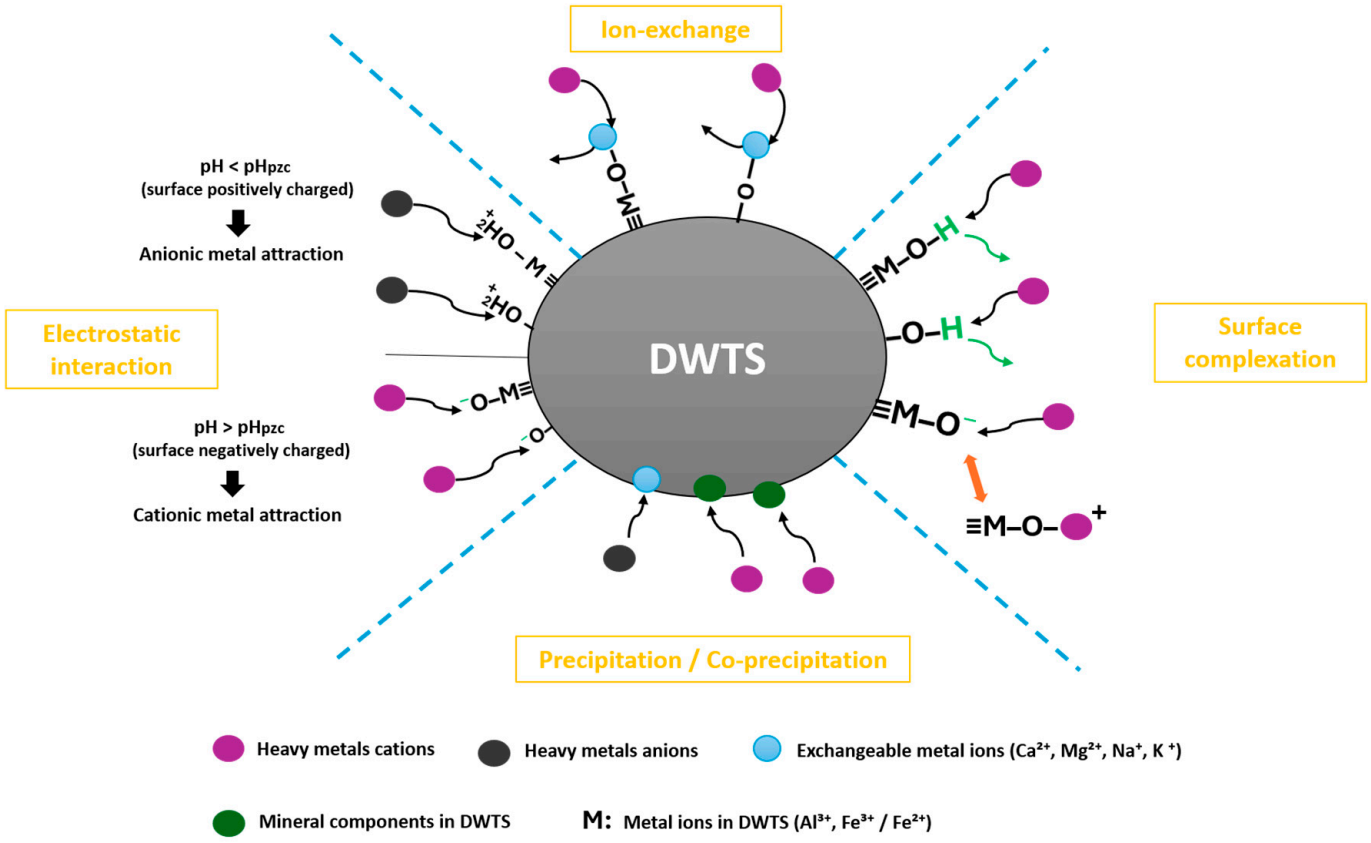


Figure 5. Schematic diagram of the mechanisms involved in heavy metal adsorption by DWTS.

Reusing DWTS eliminates many of the obstacles and serious issues related to its disposal and provides a general benefit from an environmental and economic point of view. Sludge production is largely an environmental problem before it is an economic one but its management costs may be reduced by modern reuse methods of reusing it, especially as a cheap adsorbent compared to other adsorbent materials such as activated carbon. Table 5 shows some research that explains the importance of reusing DWTS as a heavy metal adsorbent and its impact on sustainable water treatment strategy.

Table 5. Heavy metal adsorption capacities using DWTS.

Metal	Type of Sludge/Treatment	Optimal Initial Metal Concentration (mg/L)	pH Range	Adsorption Capacity/Result	Ref.
Pb, Cd and Ni	Al-DWTS fired at 500 °C	100	5.5	Adsorbed Pb (II) with a capacity of 10 mg/g (100%) Cd (II) at 9.1 mg/g (91%) Ni (II) removal with maximum adsorption capacity of 7.8 mg/(78%).	[22]
Zn and Cu	GWTPS (groundwater treatment plant sludge, dried and ground 0.5 mm)	65	Zn(II): 2.45, Cu(II): 2.15	Zn(II) and Ni (II) removal 100% at 65 ppm At 100 ppm, adsorption drops to 19 and 25% for Zn and Ni.	[106]
Cd, Cu and Zn	Granular sludge–clay (DWTS + clay, 1:2 ratio, baked at 873 K)	10	Cd (II): 4 Cu (II) and Zn (II): 5	Maximum Cd(II), Cu(II), and Zn(II) adsorption capacities of 1.53, 2.76, and 1.23 mg/g at 298 K, respectively.	[25]
As	Fe-WTS and Al-WTS		3–9	Al-WTS preferentially adsorbed As(V), Fe-WTR adsorbed As(III) more strongly (15 mg/g As(III) and As(V)).	[80]
Cu	DWTS carbonized at 600 °C + activated in a 5% NaOH		Neutral	Removal efficiency reached 98.6–99.9%.	[152]
Mo	HA-DWTRs (DWTR calcined at 600 °C + HCl 4 M activation, S/L = 1:1)	50	4	Enhanced surface area and porosity following changes, leading to improved Mo adsorption. Before alteration, the maximal adsorption capacity was 18.44 mg/g; at 25 °C it increased to 39.52 mg/g.	[26]
Hg	Al-WTRs	10–80	3–8	Strong affinity for Hg, with high sorption capacity (79.3 mg/g).	[24]
Pb and Cr	Al-DWTS		Cr (III), Pb (II): 5–6 Cr (VI): 3–4	Cr (III) removed effectively (98%), Pb(II): 82% and Cr (VI): 70%.	[16]
Pb, Cu, Ni, Cr, Zn and Co	Centrifuged WTPS		4	Removal efficiency: Pb 89.5%; Cu 94.6%; Ni 100%; Cr 84.2%; Zn 89.1%; Co 100%.	[148]
Cu, Co, Cr, Hg, Pb and Zn	Al-WTS	10	5–6 for cationic metals 2.5–4 for Cr(VI))	Maximum Pb(II), Cu(II),) and Cr(VI) adsorption capacities of 5.2 mg/g (100% removal in batch), 1.7 mg/g, 3.5 mg/g, respectively Zn(II) and Hg(II): >97% removal, Co(II): ≤80% removal.	[149]
As	Fe-GWTRs (Fe/Mn oxides)	25	4	Adsorbed As (III) with a capacity of 132 mg/g. As(V) at 77 mg/g.	[151,153]
Co	Fe/Al-SWTRs	800	6–8	Maximum capacity: 17.3 mg/g (adsorption spontaneous, endothermic).	[153,154]

Table 5. *Cont.*

Metal	Type of Sludge/Treatment	Optimal Initial Metal Concentration (mg/L)	pH Range	Adsorption Capacity/Result	Ref.
Ni and Cd	Alum sludge	1000	Ni(II): 7.94–8.12 Cd(II): 7.04–8.11	Maximum capacity for Ni: 64.96 mg/g; Cd: 45.31 mg/g.	[155]
Cu and Zn	Alum sludge	5	4–8	Cu: Removal efficiency 96.6% (max.at pH 6). Zn: Removal efficiency 97.4% (optimal at pH 6–8) limited at pH 4.	[79]

3.2.3. As a Nutrient Adsorbent

Despite being considered a waste, DWTS has shown its ability to adsorb both heavy metals and CO_2, but its adsorption benefits do not stop there. Sludge has also proven its ability to adsorb nutrients. Phosphorus is one of the most important nutrients needed by plants for growth. Research has shown that dried alum sludge can largely adsorb phosphorus. At a pH of 4, the results showed maximum adsorption values in all cases of phosphorus formation, reaching 10.2 mg/g for orthophosphate, 7.4 mg/g for polyphosphate, and for organic phosphate, the adsorption value is 4.8 mg/g (Table 6) [27]. The pH is the main factor affecting the adsorption capacity, in addition to the sludge dose used. A study by Maqbool et al. [156] reported that DWTS can adsorb ortho phosphorus with an adsorption capacity of up to 4.86 mg/g and 4.71 mg/g for condensed phosphorus.

Some techniques and tactics have been employed to alter and enhance the adsorption capacity in order to increase the adsorption efficiency of DWTS. Sludge can adsorb up to 25.32 mg/g of phosphorus when it breaks down at 800 °C because of changes in the sludge's surface characteristics [157]. By the Langmuir isotherm model, up to 98.31% of phosphorus was removed, but 77.13% of the unmodified residue was considered, the main reason being the ligand exchange and ion exchange [20]. Calcium alginate beads contain DWTS, which has the ability to adsorb 19.42 mg/g. The alginate shell contributes little to the adsorption process, but the DWTS component is essential [158].

In their investigation of the employment of denitrifying bacteria in conjunction with alum sludge ceramsite, Chen et al. [159] showed excellent pollutant removal efficiency, including 98.6% for total phosphorus, 91% for total nitrogen, and 85.8% for chemical oxygen demand. This study demonstrated how sludge ceramsite promotes. In addition to phosphorus, the ability of DWTS to adsorb nitrogen has been confirmed. A study has shown that using denitrifying bacteria with alum sludge ceramsite has the efficiency to remove pollutants. The sludge ceramist contributes significantly and effectively to increasing the pollutant removal capacity due to the formation of biofilms. The removal of ammonia and nitrate is necessary and is another area of exploration in the field of sludge reuse [159]. The modification of sludge (creation of WTR-SA beads) showed an increase in the nitrogen removal efficiency from 22.34% to 95.14%. These granules can adsorb nitrogen with a capacity of up to 2.52 mg/g (Table 6) [20]. Table 6 presents some research that explains the importance of reusing DWTS as a nutrient adsorbent and its adsorption capacity under experimental conditions.

Table 6. Adsorption capacities of DWTS for nutrient removal.

Nutrient	Chemical Form	Type of Sludge	Initial Metal Concentration (mg/L)	pH	Contact Time (h)	Adsorption Capacity	Ref
Phosphorus (P)	Orthophosphate (PO_4^{3-})	Al-DWTS	50	4	24	6.70 mg P/g	[160]
	Orthophosphate (PO_4^{3-})	Alum sludge	12.5–2000	6	48	30.83–34.53 mg P/g	[112]
	Orthophosphate (PO_4^{3-})	Al-DWTS	14.7	4	24	10.2 mg P/g	[27]
	Polyphosphate (PO_3^-)	Al-DWTS	10.8	4	24	7.4 mg P/g	[27]
	Organic phosphate	Al-DWTS	3.3	4	24	4.8 mg P/g	[27]
	Orthophosphate	Alum sludge	25	4–5.5	1.5	4.86 mg P/g	[156]
	Condensed phosphate (CP)	Alum sludge	15	5–5.5	80 min	4.71 mg P/g	[156]
	Orthophosphate (PO_4^{3-})	Modified water treatment residuals–sodium alginate beads (WTR-SA beads)	10–250	5	24	6.45 mg P/g	[20]
	Orthophosphate (PO_4^3)	Alum sludge	10–200	5	24	11.4 mg P/g	[161]
Nitrogen (N)	Ammonium (NH_4^+-N)	Modified water treatment residuals–sodium alginate beads (WTR-SA beads)	10–100	5	12	2.52 mg N/g	[20]
	Mainly ammonium (NH_4^+-N) Minor nitrate (NO_3^--N)	DWTR		neutral	1	NH_4^+-N: 0.34 → 0.0007 mg/g after 6 desorption cycles NO_3^--N: 0.009 → 0 mg/g	[162]

3.3. Recycling of DWTS in Water Treatment Processes

Recycling DWTS has a significant impact on waste reduction and improvement in water quality. Through Bensitel et al. [84], we can see the possibility of reusing DWTS through a study conducted in a drinking water treatment plant in northern Morocco. It was observed that recycling sludge contributes to reducing the need for coagulants (aluminum sulphate in this case), without affecting the effectiveness of treatment processes for water (water quality) [84]. This is consistent with the findings of Chen et al. [163], who found that by boosting particle collision and adsorption mechanisms, recycling coagulation sludge greatly increased turbidity removal in low-turbidity source water, further improving pollutant removal. In a similar study, Foroughi et al. [164] confirmed that recycling alum sludge in turbidity removal achieved a reduction rate of up to 94.81%, without worrying about aluminum and bacterial contamination (no health concerns) [164]. When powdered activated carbon (PAC) is combined with alum sludge, the turbidity removal efficiency reaches 89.2%, dissolved organic carbon reaches 52.7% and $UV_2$45 reaches 60.1%, which indicates that alum sludge contributes to improving the adsorption capacity of PAC [165].

The use of ultrafiltration in sludge recycling makes the recycling rate reach 10%. Liu et al. confirmed that this technology reduces energy consumption and makes the coagulation agitation strategy improve the sedimentation efficiency and prevent pollution [166]. These studies confirm that the recycling of DWTS contributes effectively to avoiding its disposal (reducing environmental risks), improving the efficiency of water treatment plants in addition to reducing energy consumption.

3.4. Challenges Facing the Reuse of DWTS

The utilization of DWTS for agricultural use and adsorption processes holds significant potential for enhancing efficient and effective waste management but introduces a variety of obstacles that must first be resolved in order for its extended use to become economically and socially feasible and acceptable. Despite the presence of useful nutrients such as potassium, phosphorus, and organic matter, capable of enhancing agricultural productivity and enhancing yields, concerns over the presence of deleterious impurities such as heavy metals, pathogens, and organic chemicals prevail. All these deleterious impurities have the potential to impact unfavorably on soil, root, and overall human well-being and security, respectively. In addition, its physicomechanical and chemical behavior varies with processing techniques and source water, generating uncertainty over its efficacy in enhancing agricultural land productivity. Besides these technological concerns, social and regulatory ones such as public concerns over its safety and over-regulation in its use add to its impediments towards widespread acceptance. Additionally, financial factors such as its cost in terms of transportation, processing, and logistics for its use in rural and outlying locations form additional significant impediments towards its acceptance.

The use of DWTS as an adsorbent for pollutants such as carbon dioxide, heavy metals, and nutrients, while promising, is hindered by technical and economic limitations. The improvement of adsorption capacities of sludge often involves chemical or thermal modifications, both of which can make the process costly and complex. Often, sludge-derived adsorbents must compete with conventional materials such as activated carbon, not only in terms of proven performance but also in terms of availability at an industrial level. In addition, the environmental consequences involved in transforming sludge to improve its adsorption behavior, such as secondary pollution and high energy requirements, generate concerns regarding the long-term viability of such approaches. Upscaling successful laboratory practice is an added challenge, particularly in terms of technical and financial viability. To mitigate such impediments, a techno-economic evaluation is critical, consisting of comparing the cost-effectiveness of competing approaches for sludge valorization, estimating respective environmental and public health-related risks, and suggesting policy interventions and incentives for encouraging its use. Public awareness programs for enhancing a positive outlook on the reuse of sludge will become imperative for securing social acceptance. Identification and resolution of such impediments will enable a strong platform for realizing the full potential of DWTS with reduced risk, and a sound basis can then be developed for a less environment- and economy-intensive alternative for waste management, paving the path for the following section, in which techno-economic viability of DWTS will be examined in detail.

4. Technical and Economic Considerations for DWTS Reuse

DWTS, especially alum sludge, contains aluminum, iron, and nutrients such as phosphorus and potassium that could improve soil fertility when applied to farmlands. However, heavy metals that may accumulate in the soil due to its reuse in agriculture raise concerns; hence, routine monitoring is necessary for safe application [11]. DWTS has a high content of aluminum hydroxide and a porous structure that enhances its possibilities for use in CO_2

capture by adsorption under optimized conditions. Though potential economic benefits may be associated with the use of DWTS for these purposes compared to synthetic fertilizers and traditional adsorbents, However, the economic feasibility of DWTS reuse has not been adequately studied [11].

The promise seen in small-scale applications of DWTS does not translate to large-scale installations. A seasonal variation in the composition of sludge due to different water treatment plant processes also plays a role in determining its reuse in agriculture or adsorption [11]. Some toxic elements can be released during the application of sludge, notably aluminum; these pose risks to aquatic organisms and human health and as such require detailed characterization and risk assessment studies [21,110]. The absence of a standardized life cycle assessment for DWTS reuse contributed to the reluctance of adopting life cycle assessment (LCA), yet it is vital for thorough evaluation of environmental and economic impacts. These issues show that the economic evidence on DWTS reuse remains limited and uneven across reuse pathways. Data on the costs associated with the agricultural use of sludge are not yet available, although a techno-economic assessment has been conducted on its reuse as an absorbent material [167]. In addition, there are economic assessments related to the recycling of this waste and the recovery of coagulants, but these remain tied to specific sites [13,168,169]. Future efforts should focus on relying on a specific functional unit, clearly specifying the cost year and the currency used, in order to inform and support decisions regarding the management of this sludge.

4.1. Technical Aspects

The agricultural reuse of drinking water treatment sludge has attracted much interest because it can enhance soil quality and crop productivity. The technical feasibility of DWTS mainly depends on its physical and chemical characteristics, which contain essential nutrients, such as nitrogen, phosphorus, and potassium, as well as organic matter that could enhance soil fertility [61,131,170]. It is also important to consider some conditions, such as the type of sludge and climatic conditions, because the distribution and physical application of alum sludge to the soil must be considered, as well as the effects on human health, soil, and plants. Such properties make DWTS a possible complementary soil amendment, especially in soils lacking nutrients [70].

Sandy soils have been reported to retain moisture once DWTS is introduced [21]. This allows for the establishment of roots and the uptake of nutrients. A serious technical issue that can be raised in the application of DWTS is the increased possibility of heavy metal build-up in soils. The metals in sludge, like Pb, Cd, and Hg, which are usually found in lower concentrations, may pose risks to the ecology of the soil systems and subsequently to human health [11]. Monitoring and pretreatment of DWTS will help mitigate this risk by lowering toxic components before application [61]. The application of DWTS also needs to be done based on its pH and electrical conductivity, as it will directly affect the soil and plant growth. Research has shown that alum sludge is an acidic compound that can be very beneficial in the process of alkaline soil neutralization [21].

Overly sour or salty sludge may need adjustment to avoid bad effects on crop yield and soil quality. Also, pilot studies have shown that the even application of sludge in farm fields can be achieved by using mechanized spreading techniques, thus reducing labor requirements and ensuring uniform distribution [11]. Alum sludge contains a significant amount of aluminum, due to the use of aluminum sulfate as a coagulant for water treatment [84], which provides active adsorption sites for various contaminants, including CO_2, heavy metals, and nutrients like phosphorus. Nutrient recovery is another critical application of DWTS, particularly in agricultural settings. Innovative modifications and composite development expand DWTS's versatility [20,112]. Microwave activation enhances the material's

pore size distribution and reactivity, while blending DWTS with other materials like biochar or polymer matrices improves its mechanical strength and adsorption capacity.

In CO_2 capture, DWTS exhibits impressive performance when activated thermally at 400–600 °C, which significantly improves its pore structure and surface functionality. Studies have shown that such treatments can achieve adsorption capacities reaching 2.5 mmol CO_2 per gram of sludge [23]. Chemical modifications, including acid activation and impregnation with amine-based compounds, further increase the efficiency and selectivity of DWTS for CO_2 capture, making it competitive with commercially available adsorbents such as zeolites, silicon compounds, activated carbons, or metal oxides [171–174]. In wastewater treatment, DWTS demonstrates exceptional potential for heavy metal adsorption. Metals such as Pb, Cd, and Hg are effectively removed through processes like ion exchange, surface complexation, and electrostatic interactions. Thermally activated DWTS has been shown to achieve removal efficiencies of over 90% for these contaminants, with adsorption capacities often exceeding 10–79.3 mg/g, depending on the treatment conditions [22,24,175]. Studies also show the maximum efficiency of DWTS in removing As, Cr, Ni, Se and Cu from aqueous solutions, which provides a benchmark and sustainable alternative to other sorbents. Some studies have reported that modified DWTS can help reduce arsenic concentration to maximum limits. Under optimized experimental conditions, selenium removal efficiency exceeds 80% [69].

4.2. Economic Aspects

Economically, González et al. assessed DWTS-based granules production for reuse in pollutant control, followed by transportation and application [167]. Costs were expressed in U.S. dollars per ton of sludge (USD/t) based on 2025 prices, with the consumer price index used to adjust them. The total annual cost was calculated as the sum of the annual capital cost (CAPEX multiplied by a capital recovery factor, over 15 years at a discount rate of 7%) and the operating costs (OPEX). Furthermore, a change in natural gas prices and bentonite (±30%) leads to a change in granulation costs (±24%) according to the sensitivity analysis. On the other hand, specifically in Morocco, Bensitel et al. [169] presented an assessment of the DWTS (in Al Hoceima) based on a functional unit of 1 m^3 of treated water and a specific system scope, concluding that sludge production is the primary source of environmental impacts at the drinking water treatment plant. Table 7 summarizes the costs reported in studies related to the management and reuse of DWTS.

The economic benefit of using DWTS in agriculture, particularly as waste-derived fertilizers instead of synthetic ones, depends on a balance between the costs of sludge management and the benefits derived from its application. Sludge disposal techniques like landfilling and incineration have historically come with hefty costs and negative environmental effects. However, by turning a waste product into a resource, DWTS reuse as a soil supplement may provide a more affordable option [21,28]. One of the most important economic benefits is the reduction of landfill and disposal costs. Water treatment plants often charge high fees for landfill sludge disposal, which can be mitigated by reusing the sludge for agricultural use. In areas with high agricultural activity, it has been demonstrated that reusing alum sludge for soil enhancement can reduce disposal costs [11,64]. For example, in the United Kingdom, landfill fees for inert waste rose from approximately £8 per ton in 1996 to about 90 pounds in 2018 [176]. According to 2010 prices, non-hazardous waste disposal cost $59.99/t in the USA [177]. Landfill disposal of alum sludge in Victoria (Australia) was reported to cost $130–200/ton, excluding transport [13]. Important elements like potassium and phosphate are found in DWTS, but they cannot replace commercial fertilizers [70,170]. Studies indicate that the application of DWTS to nutrient-deficient soils not only may improve crop yields but also reduces the reliance on expensive chemical in-

puts [21]. Sludge's high moisture content is a problem because it raises transportation costs; however, this load can be greatly lessened by implementing dewatering technology. Road transport costs of 30–40 AUD/t, depending on distance, were reported in Australia [13], and $0.37 per wet ton per mile (2007 USD) in the USA [177]. The infrastructure needed for widespread implementation is another important consideration. To guarantee the viability of DWTS reuse projects, investments in sludge spreading equipment and farmer training are required [11]. Even though these upfront costs could be high, they may eventually be balanced by long-term financial gains, including better soil health and less reliance on fertilizer [28].

As a waste material, DWTS may represent a lower-cost alternative to adsorbent materials like zeolites, silicon compounds, activated carbon, and metal oxides [171–174,178]. It has been observed in studies that DWTS can adsorb significantly under experimental conditions, which gives a good impression of its strong commercial potential. The inherent nature of the material, like aluminum and iron hydroxides, provides adsorption capacity. However, the conversion of DWTS into granular adsorbents involves conditioning and granulation costs. In the Chilean case study, these costs ranged from 135 to 190 USD/t, which is of the same order of magnitude as the cost of transport and landfill disposal; calcination and binder consumption accounted for more than 70% of the operating cost. The resulting application costs were 0.10–0.19 USD/m^3 of water treated for arsenic, 0.10 USD/m^3 for copper, and 370–530 USD/kg of phosphorus removed [167]. Recycling DWTS helps to mitigate the carbon footprint of various industries by engaging in greenhouse gas abatement activities that may translate into economic gains via carbon credits and tax incentives.

The recycling of DWTS within the treatment plant can also reduce operating costs. At the Al Hoceima plant (Morocco), a preliminary estimation showed a total reagent cost of 37,900.87 and 10,308.74 USD in the sludge recycling scenarios, compared with 134,080.10 USD under current operation [169]. For coagulant recovery, acid extraction was estimated to require a capital cost of $6–7 million and an operating cost of $80–100/t of sludge (20% dry solids) for a plant treating 3000 t of dry solids per year, with 80% alum recovery [13]. Coagulant recovery is not always cost-effective; a study reported a cost of 257.30 USD/t for selective recovery, compared with 186.40 USD/t for haulage and landfill [13], and the operating costs of recovery by pressure filtration, Donnan dialysis, and electrodialysis (£61–84 per 1000 mol of metal) were comparable to those of purchasing fresh coagulant (55–80 per 1000 mol) [168].

The utilization of DWTS is of significant economic advantage over conventional treatment methods for heavy metal adsorption. The heavy metals Pb, Cd, and Hg can be effectively removed from industrial wastewater by the process of DWTS, without using costly chemical reagents and filtration equipment. With the use of sludge, which is readily available as waste material, industries can meet environmental standards simultaneously while reducing costs [20,22]. Scientific studies have established that DWTS-based adsorbents have the capability of reducing the amount of heavy metals to levels acceptable to regulatory requirements. DWTS can also be used as an inexpensive source of phosphorus and potassium, thereby decreasing the reliance on chemical fertilizers.

Considering the state of affairs and the anticipated trend for the future, significant efforts and studies must be conducted worldwide to explore the potential positive uses of sludges while critically evaluating the potential drawbacks of such agricultural and adsorption applications.

Table 7. Reported costs of DWTS disposal, reuse as adsorbents, and recycling or coagulant recovery.

Option	Reported Cost	Functional Unit/Basis	Currency, Year	Country	Ref.
Disposal and transport					
Landfill disposal	$130–200/t (transport excluded)	t of sludge	AUD (report 2015)	Australia	[13]
Road transport	30–40 AUD/t	t of sludge			
Transport	$0.37 per wet ton	wet ton × mile	USD 2007	USA	[177]
Disposal	$59.99/t	t	USD 2010		
Landfill gate fee (inert waste)	£8/t (1996) to £90/t (2018)	t	GBP	UK	[176]
Reuse as adsorbent					
Conditioning (dewatering)	50–80 USD/t	t of DWTS	USD 2025	Chile	[167]
Granulation	90–140 USD/t	t of DWTS			
Application of granules	As: 0.10–0.19 USD/m^3 Cu: 0.10 USD/m^3 P: 370–530 USD/kg removed	m^3 of water; kg of P removed			
Recycling and coagulant recovery					
Sludge recycling in the plant	10,308.74–37,900.87 USD with recycling vs. 134,080.10 USD (current operation)	total reagent cost; period not specified	USD	Morocco	[169]
Alum recovery (acid extraction)	Relative CAPEX: $6–7 M Relative OPEX: $80–100/t sludge (20% DS)	plant of 3000 t DS/year	AUD (report 2015)	Australia	[13]
Selective recovery vs. haulage and landfill	257.30 vs. 186.40 USD/t	t of sludge processed	USD		

5. Research Priorities and Future Challenges

Recycling of DWTS for adsorption and agricultural uses is an interesting but daunting prospect that requires significant technological innovations and process optimization to improve its efficiency and feasibility for large-scale application. Many studies illustrate the ways sludge can be used, although there are still considerable challenges to its more widespread use. To address these issues, we need a strategy that includes developing more effective material transformation methods, improving processing techniques, and fully investigating environmental and economic factors to enable sustainable, practical use. One of the most important aspects is to optimize its physicochemical characteristics for its efficiency in applications. Alum-based sludge has been subjected to tremendous research regarding adsorption capacity in detoxifying contaminants such as heavy metals, phosphorus, organic pollutants, and CO_2 from wastewater and air [166,179]. However, the raw DWTS has poor adsorption capacity owing to limited surface area, low porosity, and few active sites. Therefore, several modification techniques have been proposed to augment its performance. Thermal activation procedure, acid and alkali treatment, and incorporation of functional materials such as biochar, graphene oxides, and metal oxides have been investigated to improve the specific surface area and expand the availability of binding sites for pollutants. Surface treatment with acids or bases was reported to improve

the cation exchange capacity and form more reactive binding sites to improve the efficacy of DWTS in immobilizing a wide variety of contaminants [25,150]. However, although promising results have been shown in laboratory-scale experiments, the scalability of these treatments is difficult, and pilot-scale and field trials are required to test their feasibility under real conditions [150,179].

In farm use, DWTS has been of value because of its properties of retaining nutrients, such as phosphorus and organic matter. But this application also has potential risks and uncertainties that have to be exhaustively dealt with before it is applied on a large scale. One of the main concerns is the accumulation of heavy metals in soil, which can lead to long-term pollution and toxicity hazards to crops and human health. Also, long-term field trials need to be done to observe how stable DWTS is in the soil, how susceptible it is to erosion, and how it reacts with other types of soil and weather conditions. Lack of such tests will make large-scale application as an amendment in the soil unclear, since regulators and farmers need large sets of data to verify its efficacy and safety [16,180].

Although DWTS reuse may be endowed with technological and environmental benefits, the infrastructural and logistic aspects, such as transport, processing facility needs, and regulatory costs. Motivations, limited economic prospects, combined with slow industrial growth for sludge-based technologies for policymakers and industries, would, in turn, severely constrain their actual application, even when being environmentally friendly. The absence of a global database documenting the yearly production, characteristics, and reuse potential of DWTS on a country, regional, and continental basis inhibits the development of standardized management practices and their optimum utilization [181]. A worldwide production database would be central to fostering effective regulatory frameworks, public awareness campaigns, and extensive implementation strategies. This would serve to close the gap between industrial uptake and scientific research so that DWTS is incorporated into green waste management policies effectively. LCA studies aimed at the reuse of DWTS in agriculture and adsorption are exceedingly limited, which makes it difficult to quantify the environmental and economic tradeoffs involved in its valorization. It could be a collective description of the environmental footprint by assessing contributors such as greenhouse gas emissions, energy consumption, water usage, and waste generation over the life cycle. Such an approach, in this respect, serves as a key factor in determining whether the environmental benefits outweigh the potential negative aspects of sludge valorization, so that due consideration can be given to the sustainable development goals.

The potential benefits are mitigated by increasing concerns regarding contaminant accumulation, toxicity risks, and possible regulatory compliance. Therefore, an SEA report must be prepared whenever DWTS-based applications are allowed, so that long-term ecological and health hazards associated with heavy metals, pathogens, and residual chemical additives are avoided [140,182]. Field studies of long duration are required to assess the associated risks. Land application can also change soil pH and the microbial community, which can have preeminent effects on nutrient cycles, crop uptake, and soil fertility thereafter. In applications of adsorption, a chief environmental concern, however, is what happens to the spent adsorbents after application. DWTS-based adsorbents, while being saturated by the pollutants, would, thereafter, have to be properly discarded or regenerated to avoid secondary pollution. With inappropriate disposal options, adsorbed contaminants could be released back into the environment, countering the merits of their removal in the first place. DWTS regeneration through thermal or chemical desorption techniques may prolong the lifespan of the adsorbents, but they need optimization to reduce energy consumption and secondary waste products [183]. Another important concern with DWTS involves the presence of aluminum; studies have associated chronic aluminum exposure with neurotoxicity and potential health disorders [184,185]. Consideration of direct expo-

sure risks to consumers through agricultural products is controversial. Although there is a rising interest in valorization of DWTS for use in agriculture, adsorption, and construction applications, significant regulatory gaps, market challenges, and inconsistent policy efforts act to moderate its unrestrained acceptance. Designating a clear legal framework, an economic incentive, and a guiding standard is paramount to promote safe, effective, and viable commercialized use of this sludge. One of the major hindrances to valorization is its classification as industrial waste instead of a recoverable resource. A multitude of waste management legislations across multiple countries classify DWTS as hazardous or non-hazardous waste and introduce strict disposal practices that usually inhibit further repurposing. Policymakers should come up with clear and evidence-based regulatory frameworks that would provide limits on contaminants, guidance on the application, and risk assessment procedures for various reuse pathways in the domain of diversion from current disposal methods.

Economic aspects studies are key to defining the cost–benefit dynamics of DWTS reuse versus conventional materials. The idea that sludge is merely waste—and not a resource—will often create resistance among farmers, industries, and even policymakers, leading to slower adoption rates. An education campaign with high visibility, scientific outreach or real-world examples may help in building the confidence and demand for sludge-based innovations. To this end, the development of international partnerships between regulators, research organizations, and private enterprises could bring about the development of global best practices, the sharing of information, and the harmonization of policy platforms on DWTS valorization.

6. Conclusions

As potable water production in treatment plants increases, sludge generation is also expected to rise. The substantial growth of the global population presents a clear challenge for potable water management and the reuse of waste from treatment processes. It is necessary to enhance water quality and expand access so more communities can benefit from potable water. Additionally, reusing DWTS should be explored across all possible avenues to maximize benefits and support the circular economy. Sludge valorization plays a vital role in sustainable waste management; thus, proper characterization of sludge is crucial for its effective reuse. Understanding the physical and chemical properties of sludge, such as water retention capacity, pH, and soil porosity, helps optimize reuse strategies, especially in agricultural applications and adsorption processes. Despite progress, many gaps remain, especially regarding the heterogeneity of sludge composition, metal toxicity to plants, the impact of sludge on soil properties, nutrient and organic matter uptake, and whether it benefits the surrounding soil. The interaction between geological materials and water, as well as the potential accumulation of radioactivity in DWTS, should also be considered. Given the revealed adsorption potential of sludge, research should focus on identifying effective properties for CO_2 adsorption, an area with limited studies, as well as pollutant and heavy metal sequestration. Studies indicate that heavy metal concentrations in DWTS are lower compared to sewage sludge, highlighting its positive role in adsorption after compositional analysis. However, challenges include the lack of comprehensive life cycle assessments, systematic management strategies, and unified standards for DWTS reuse. While a single solution may not exist, a multidisciplinary approach is essential. Developing better characterization criteria will help understand sludge properties, and collaboration among researchers, policymakers, treatment plant operators, and government officials is crucial to promote awareness of these benefits. Reusing DWTS not only solves disposal issues but also facilitates resource recovery, marking a significant step toward sustainable resource management and a circular economy.

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Abbreviations

The following abbreviations are used in this manuscript:

DWTS	Drinking Water Treatment Sludge
WHO	World Health Organization
UV-LEDs	Ultraviolet irradiation using Light-Emitting Diodes
APOs	Advanced Oxidation Processes
WTR	Water Treatment Residuals
WTS	Water Treatment Sludge
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
ATR-FTIR	Attenuated Total Reflectance–Fourier Transform Infrared Spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy
TEM	Transmission Electron Microscopy
BET	Brunauer–Emmett–Teller
SCWO	Supercritical Water Oxidation
PAC	Powdered Activated Carbon
LCA	Life Cycle Assessment
SEA	Strategic Environmental Assessment

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