

Article

Experimental Study on the Application of Sludge from Water Treatment Plant as a Reagent for Phosphate Removal from Wastewater

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Abstract: The paper presents the results of laboratory studies on the removal of phosphate in a wastewater treatment plant by adding sludge formed at the water treatment plant (water treatment sludge—WTS) in the city of Astana (Kazakhstan). Raw WTS from the sludge drying beds was used in the study, and the content of chemical compounds present in the dry sludge residue was determined, yielding 10.8–14.6% aluminum oxide (Al_2O_3) and 4.58–5.31% iron oxide (Fe_2O_3). The sludge moisture ranged from 90.5 to 95.6%, and the ash content ranged from 51.3 to 63.9%. The raw sludge from the WTP was added to the wastewater collected before the sand trap and after biological treatment. On the basis of the obtained test results, it was found that the effect of phosphate removal depended primarily on the sludge dose and was above 90% when adding 50 mL of sludge to 1 L of sewage. To a lesser extent, the effect of phosphate removal was dependent on the contact time of the sludge with the wastewater and the place where the wastewater sample was taken.

Keywords: water treatment sludge; alum sludge; phosphate removal; reuse; wastewater treatment



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1. Introduction

Providing clean and safe drinking water to all residents is one of the most important tasks of municipal services. However, the quality of available raw water resources, especially surface water, requires the use of treatment technologies, among which coagulation with the use of aluminum and iron salts predominates [1]. Sludge generated during the treatment of drinking water, hereafter referred to as water treatment sludge (WTS), and its management can be a serious environmental problem, both in terms of the amount of sludge generated and how it is managed.

For example, the US EPA estimates that large water treatment plants (WTPs) serving cities with populations of 100,000–500,000 inhabitants generate 200,000 tons of WTS per year [2], and the daily global production of WTS can reach as much as 10,000 tons [3]. Sludge from WTPs mainly contains hydrolysis products of used coagulants, residues of other chemicals used during treatment (polymers), organic substances (humic colloids, microorganisms, plankton), and other substances that have been removed from water (insoluble or poorly soluble metal salts and others). It should be noted here that the quantity and composition of WTS depend largely on the quality of raw water and the chemicals used during its treatment [4,5].

For many years, WTS was treated as environmentally neutral, and therefore, the primary method of its disposal was the discharge directly into the aquatic environment [6]. Despite the risks associated with the possible accumulation of aluminum, iron, and other metals in aquatic organisms and, consequently, in humans, this method is still widely

used, especially in developing countries where there is a lack of adequate environmental regulations [4,5]. Another frequently used method of WTS disposal is to discharge it to the sewer system and then to the wastewater treatment plant (WWTP). This method can be beneficial to the efficiency of removing organic compounds and phosphorus from wastewater, but it also carries the risk of increasing the amount of sludge generated in the sewer system and WWTP, as well as interfering with wastewater and sludge treatment processes [7,8]. The most common method of WTS disposal is its storage on sludge drying beds, but this method also has numerous limitations related to the increasingly strict environmental regulations related to waste management and limited availability of storage space [4,6,9]. Therefore, in recent years, there has been an increased interest of researchers in the problems of sludge management that are consistent with the principles of sustainable development. Nguyen et al. [10] estimated that 197 scientific articles related to the subject of WTS were published in the period of 2000–2021. Most of them refer to the possibility of recycling, reuse, and recovery (the “3R” concept), i.e., sustainable solutions and the circular economy, as an alternative to the traditional “Take-Make-Dispose” approach (linear economy).

Most potential applications of WTSs are related to their reuse in water and wastewater management, agriculture, and construction. Many studies have confirmed the usefulness of WTS as a coagulant and adsorbent of pollutants in wastewater treatment. Guan et al. [11] reported an improvement in chemical oxygen demand (COD) removal of 20% and suspended solids removal of 15% by adding WTS containing insoluble aluminum hydroxides (hereinafter referred to as alum sludge) to the raw effluent in the pre-treatment stage, while Nair and Ahmad [12] used alum sludge in the treatment of wastewater after the UASB reactor, achieving a COD removal effect of 74% and turbidity of 89%.

The vast majority of these works deals with the adsorption properties of WTS and its use for phosphorus removal from wastewater. The processes of adsorption of phosphorus and other metals on sludge from water treatment plants have been the subject of many studies, which have shown that its mechanism can consist of unit processes such as surface deposition, ligand exchange, electrostatic attraction, ion exchange, chemical reactions with coprecipitation, and complexation (Figure 1). Yang et al. [13] showed that ligand exchange is the dominant process here, with a smaller contribution from ion exchange (involving humic ions) and a minor contribution from chemical and coprecipitation processes. The primary importance of ligand exchange for phosphorus adsorption has also been confirmed in other studies, not only relating to WTS [6,14] but also other adsorbents (composite, fibrous, etc.) [15,16]. The results confirm that alum sludge is a potentially good adsorbent of phosphate in wastewater, with an adsorption capacity of 2–43 mg P/g alum sludge [10] and phosphorus removal efficiency even above 96% [6,17–19]. Other studies have confirmed the effectiveness of using WTS in treating textile wastewater to remove dye [20] or heavy metals, such as Zn, Cu [21], As [22,23], Cr, Pb, and others [10].

There have also been a number of papers showing the feasibility of using WTS in the construction industry [24], e.g., for the production of bricks [25], concrete and mortar [26], cement [27], and light aggregate [28]. Another sustainable approach to the disposal of sewage sludge from WTP is its use in agriculture and land-based applications for various purposes, including improving soil aggregation, increasing moisture holding capacity and permeability, or using WTS as a soil conditioner and ameliorant [1,4,29].

Modern requirements related to the protection of surface waters against eutrophication require the use of technological processes that ensure the removal of nitrogen and phosphorus from wastewater. In developing countries, such as Kazakhstan, the majority of wastewater treatment plants are facilities built in the 1960s–1980s that use traditional activated sludge technology without the removal of nutrients [30]. In such a situation, one of the most economical and rational solutions for the removal of phosphorus (considered a key element causing eutrophication of freshwater bodies) is the use of a chemical method with aluminum, iron, or lime salts as coagulants. WTS, as a waste containing large amounts of aluminum and iron hydroxide, can be both a raw material for the recovery

of pure coagulant, as well as replace, in raw or modified form, commercially available reagents (coagulants), thus reducing the operating costs of WWTPs [1].

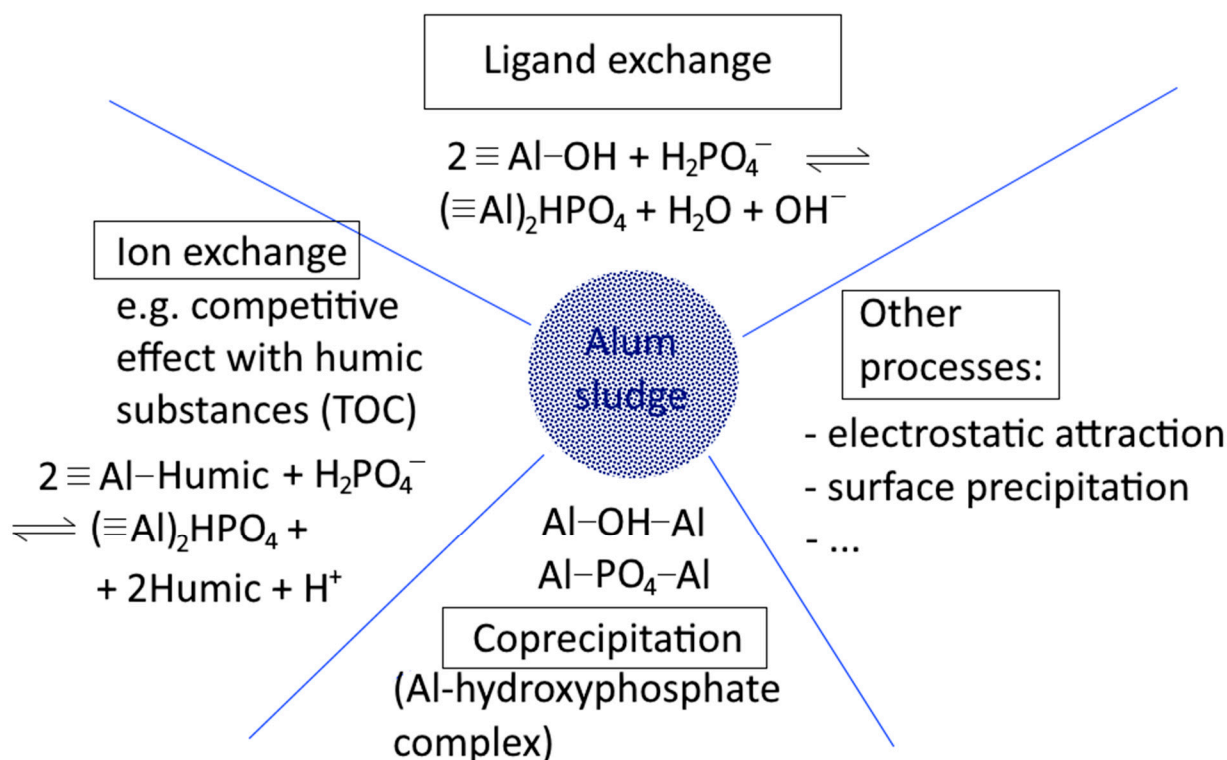


Figure 1. Mechanism of phosphate adsorption on alum sludge.

The purpose of this study was to investigate the possibility of phosphate removal in municipal wastewater treatment plants by adding raw, not regenerated, WTS. Although there are many examples in the available literature of the effectiveness of WTS as a reagent used to remove phosphorus from wastewater, most of the studies in this area have been conducted using synthetic wastewater [6], without reference to a specific technological system of the WWTP, which makes it difficult to use the results of these studies in practical applications. The presented study is an attempt to fill this gap and may contribute to the use of WTS for phosphorus removal on a technical scale in operating wastewater treatment plants.

2. Materials and Methods

The Astana City Water Treatment Plant is the main facility supplying the capital of Kazakhstan with drinking water and water for industrial purposes. Raw water is supplied to the plant via three transmission pipelines with diameters of 1000 mm (2 lines) and 1200 mm (1 line) from the Astana 3 (Vyacheslav) surface water reservoir, located 51 km southwest of the city. The reservoir is designed for the long-term flow regulation of the Yesil River. The total capacity of the reservoir is 410 million m³, and the minimum available resources in dry years are 67.2 million m³/year.

The technological processes of water treatment include sedimentation, filtration, and disinfection and are carried out in two main technological lines: line no. 1, commissioned in 1968–1984 with a capacity of 200,000 m³/d, and line no. 2, commissioned in 2011 with a capacity of 105,000 m³/d. Line no. 1 consists of mixing chambers (2 units), settling tanks with a reaction chamber (20 units), and sand filters (10 units). Line no. 2 consists of fast-mixing chambers (2 units), flocculation chambers (6 units), settling tanks (6 units), and rapid sand filters (12 units).

The following reagents are used for treatment: sodium hypochlorite—NaClO (for pre-chlorination in mixing chambers and disinfection of treated water), polyaluminium

chloride—AlCl₃HO (coagulant), and flocculant Praestol-650 TR (copolymer of acrylamide with cationic acrylic acid derivative). The treated water is stored in 4 reservoirs of 20,000 m³ each and then supplied by a pumping station to the water distribution network of Astana.

The sludge generated in the treatment process is retained in the horizontal flow settling tanks, which are equipped with mechanical sludge scrapers and continuously discharged directly to the thickeners. In addition, WTS is generated by backwashing the filters. Backwashed water is discharged through a common gravity sewer to lamella (thin-layer) separators, where flocculant-assisted sedimentation takes place. Supernatant water is collected in a storage tank and pumped to the head of WTP, while sludge from separators is discharged by gravity to thickeners. To further reduce the volume, the thickened sludge is transported to the dewatering station, where the sludge is further reduced in hydration on belt presses. The dewatered sludge is transported to the sludge drying beds, where it is dried (Figure 2). Currently, sludge drying is the last stage of its disposal.



Figure 2. Sludge drying beds of the Astana WTP (photographed by S. Merkýreva, 2022).

The average daily amount of sludge delivered to thickeners is 4651 m³/d, of which 4020 m³/d is the sludge retained in settling tanks and 631 m³/d is the sludge from backwashed water separators.

The possibility of using WTS as a reagent supporting the removal of phosphorus from wastewater was analyzed at the wastewater treatment plant in Astana, which is a facility with an average daily capacity of 254,000 m³/d and traditional mechanical and biological treatment technology supported by additional treatment in flotation filters. Mechanical treatment takes place in the screening room with a pumping station, horizontal sand traps, and primary settling tanks with a diameter of 28 m. Sand retained in sand traps is dried on drying beds. The biological treatment takes place in multistage-activated sludge tanks with separate zones for nitrification and denitrification, followed by radial clarifiers with a diameter of 28 m. After the clarifiers, wastewater is treated in 32 flotation filters, to which coagulant and flocculant are added to aid in the removal of residual suspended solids as well as nitrogen and phosphorus compounds. The final stage of treatment is ultraviolet disinfection, after which the treated wastewater is discharged by pumps into the Yesil River. Sewage sludge generated in the treatment process is gravitationally thickened and then mechanically dewatered.

The scope of the conducted research included the following:

- Analysis of the quality of raw water from the Astana 3 reservoir (Vyacheslav);
- Analysis of the quality of treated water taken from clean-water tanks;
- Analysis of hydration and ash content in WTS;
- Analysis of the chemical composition of the dry sludge residue of WTS;
- Qualitative analyses of wastewater samples mixed with WTS at different contact times.

Sampling for the surface water quality analysis of the Astana reservoir was carried out manually at a depth of 1 m in accordance with the requirements of normative documents [31,32]. Sampling of WTS from the sludge drying beds of the WTP was carried out manually in accordance with generally accepted principles.

The analytical tests were carried out in the laboratory of the Astana WWTP. The hydrogen index pH was determined using the potentiometric method, while the total dissolved solids and suspended solids, sulfates, total sulfur content, fats, and oils were evaluated using the gravimetric method [33]. The photometric method was used to determine nitrates, nitrites, ammonium ions, cyanides, and phenol [33]. Dissolved oxygen, biological oxygen demand, and chemical oxygen demand were determined using the titration method [34].

First, moisture and ash content tests were performed in order to determine the water content and the ratio of organic and mineral parts in the WTS samples, respectively (Figure 3). Ash content was determined in accordance with the method described in [35].

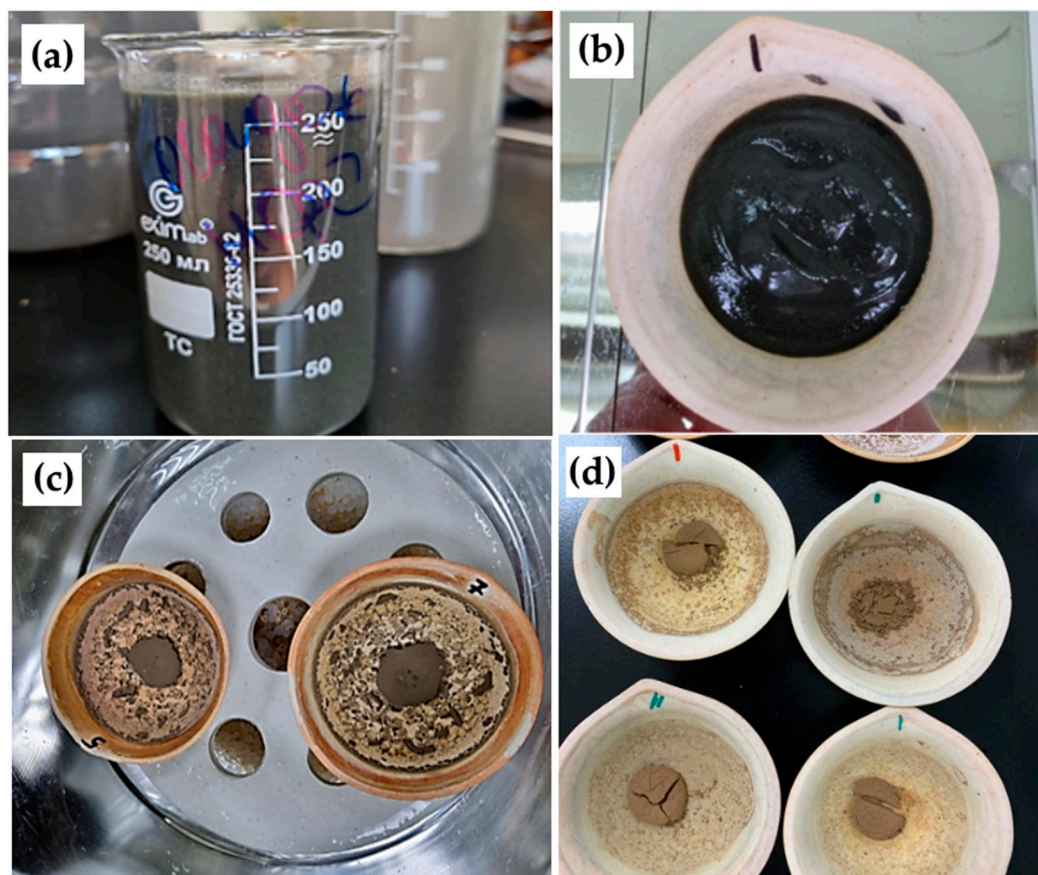


Figure 3. WTS at different stages of the studies: (a) raw WTS taken from sludge drying beds at Astana WTP; (b) prepared for moisture and ash content tests; (c) dried for hydration testing; (d) dried after calcination for ash content testing.

To analyze the effect of WTS dosage on the efficiency of phosphorus removal from wastewater, the following methodology was used: wastewater samples from Astana WWTP with a volume of 1.0 L each were taken before the sand trap and after biological treatment (secondary clarifiers), and then, non-regenerated WTS from Astana WTP was added to them at doses of 5, 10, 20, and 50 mL, respectively. The test samples were mixed thoroughly and left for

30 and 60 min. The samples were periodically shaken to simulate the movement of wastewater in the WWTP. The following indicators were determined in each of the tested samples:

- Phosphate (using the photometric method [36]);
- Iron (using the atomic emission spectrometry method [37]);
- Aluminum (using the photometric method [38]);
- Suspended solids and dry residue (using the gravimetric method [39]).

Potentiometric, polarographic, and atomic spectrophotometry methods were used to determine the content of chemical compounds present in the dry residue of WTS [40].

3. Results and Discussion

3.1. Characteristics of Surface and Treated Water and WTS

The results of the qualitative analysis of surface water collected from the Astana reservoir and treated water from the Astana WTP compared to the standards enforced in Kazakhstan are shown in Table 1.

Table 1. Results of the analysis of surface water quality from Astana reservoir and treated water from Astana WTP.

Parameter	Unit	Surface Water	Treated Water	National Standard for Drinking Water
turbidity	NTU	0.8	0.5	1.5
color	Pt Co	10	5	20
odor	-	very weak	very weak	weak
taste	-	-	no taste	very weak
pH	-	7.65	7.92	6.0–9.0
alkalinity as CaCO ₃	mg/L	150	145	-
oxidizability	mg/L	2.8	2.8	5.0
hardness as CaCO ₃	mg/L	225	250	350
chlorides	mg/L	74.0	97.0	350.0
sulfides	mg/L	65.8	84.0	500.0
dry residue	mg/L	444.2	498.0	1000.0
fluorides	mg/L	0.24	0.30	1.2
polyphosphates	mg/L	<0.05	<0.05	3.5
nitrates	mg/L	0.49	0.86	45.0
nitrites	mg/L	0.021	0.005	3.0
aluminum	mg/L	-	0.02	0.5
ammonia	mg/L	0.05	<0.05	2.0
sodium	mg/L	48.4	71.4	200.0
potassium	mg/L	3.3	3.8	-
magnesium	mg/L	14.8	17.3	-
calcium	mg/L	52.2	40.0	-
iron	mg/L	0.045	0.066	0.3
manganese	mg/L	0.008	0.009	0.1
lead	mg/L	-	0.004	0.03
copper	mg/L	-	0.0046	1.0
zinc	mg/L	-	0.015	5.0
residual free chlorine	mg/L	-	0.80	0.3–0.5
residual fixed chlorine	mg/L	-	0.30	0.8–1.2
BOD ₅	mg/L	1.3	-	-
dissolved oxygen	mg/L	7.4	-	-
saprophytic microorganisms, T = 22 °C	number/L	>300		
saprophytic microorganisms, T = 37 °C	number/L	>300		

After analyzing the obtained data, the following can be seen:

- The surface water of the reservoir corresponds to a neutral or slightly alkaline environment;

- The contents of sulfates, chlorides, nitrogen compounds, heavy metals, and microbiological indicators do not exceed the standards for surface water and drinking water.

The results of the moisture content tests of WTS ranged from 90.5 to 95.6%, which indicates partial dewatering of the sludge in the process of gravitational thickening and drying. In turn, the ash content was 51.3–63.9%, which means that most of the substances contained in the WTS were the mineral fraction. The qualitative analysis of the dry sludge residue showed a significant concentration of silicon, aluminum, and iron oxides, which is related to the aluminum coagulant and flocculant used in the treatment process (Table 2). The examined sludge properties confirmed its potential suitability for use as a coagulant supporting the precipitation of phosphorus in wastewater.

Table 2. The results of the qualitative analysis of the dry sludge residue from the WTP.

Parameter	Percentage
aluminum oxide (Al_2O_3)	10.8–14.6
iron oxide (Fe_2O_3)	4.58–5.31
potassium oxide (K_2O)	1.64–1.98
silicon oxide (SiO_2)	49.86–53.3
phosphorus oxide (P_2O_5)	0.2–0.3
magnesium oxide (MgO)	1.74–2.16

3.2. Results of Laboratory Tests of Wastewater Samples with WTS Additive

In the first stage, 5, 10, 20, and 50 mL of sludge were added to respective containers of 1 L of wastewater collected before the sand trap. Figure 4a shows that as the volume of added sludge increases, the turbidity of the tested samples visually increases. In addition, the quality of the filtrate from the prepared samples was visually examined after 30 and 60 min of contact time (Figure 4b,c), which showed that, in both cases, they had very similar turbidity.

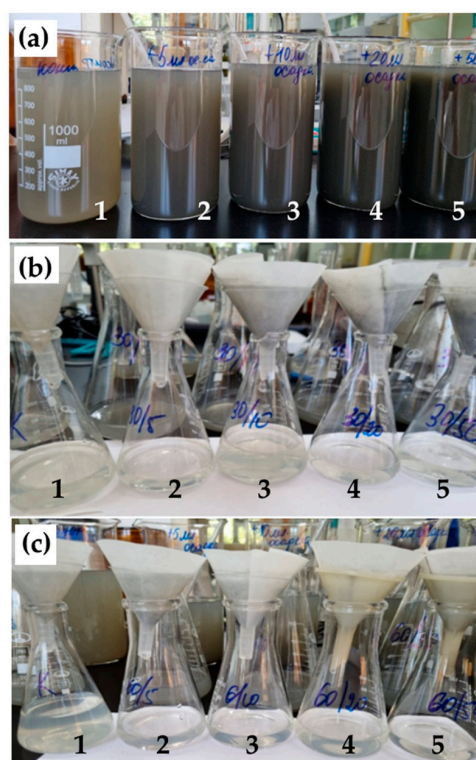


Figure 4. Turbidity assessment: (a) test sample—wastewater sample mixed with WTS; (b) filtrate of the test sample after 30 min of contact; (c) filtrate of the test sample after 60 min of contact (samples description: 1—wastewater without the addition of WTS/control sample; 2—wastewater + 5 mL of WTS; 3—wastewater + 10 mL of WTS; 4—wastewater + 20 mL of WTS; 5—wastewater + 50 mL of WTS).

The results of laboratory analyses conducted to determine phosphate, iron, aluminum, suspended solids, and dry residue after 30 and 60 min of contact are shown in Table 3.

Table 3. Laboratory results of wastewater samples collected after the sand trap with WTS added.

Parameter	Control Sample	Contact Time—30 min Volume of WTS Added				Contact Time—60 min Volume of WTS Added			
		5 mL	10 mL	20 mL	50 mL	5 mL	10 mL	20 mL	50 mL
WTS collected on 26 August 2022; WTS moisture content—95.6%									
phosphate, mg/L	11.09	-	6.30	3.97	1.45	-	5.61	3.53	1.07
iron, mg/L	3.06	-	8.82	15.88	29.99	-	9.41	19.11	33.52
iron(2) *, mg/L	1.35	-	0.71	0.82	0.94	-	0.94	1.06	1.76
aluminum, mg/L	1177	-	1170	1140	1143	-		1157	1153
dry residue, mg/L	280	-	921	1196	2184	-	-	-	-
suspended solids, mg/L	3.06	-	8.82	15.88	29.99	-	9.41	19.11	33.52
WTS collected on 31 August 2022, WTS moisture content—95.6%									
phosphate, mg/L	8.95	5.36	4.60	1.83	0.88	6.05	4.16	2.14	0.76
iron, mg/L	2.12	6.00	8.94	16.46	37.04	7.53	8.11	15.58	31.75
iron (2) *, mg/L	1.18	1.06	1.41	1.52	1.52	1.06	1.18	1.29	1.41
aluminum, mg/L	0.07	4.80	25.10	32.30	38.40	10.50	29.40	31.90	39.90
dry residue, mg/L	1040	1050	1053	1013	1027	1033	1043	1030	1037
suspended solids, mg/L	215	492	1020	1102	2267	-	-	-	-
WTS collected on 02 September 2022, WTS moisture content—90.5%									
phosphate, mg/L	11.59	8.00	5.29	2.84	0.63	7.88	5.17	2.71	0.63
iron, mg/L	5.94	8.11	15.29	24.70	31.75	16.22	31.40	37.34	81.14
iron(2) *, mg/L	0.71	0.71	0.71	0.59	0.82	0.88	1.30	1.76	1.12
aluminum, mg/L	0.08	23.6	30.6	38.6	45.0	25.0	28.2	38.8	48.8
dry residue, mg/L	1113	1077	1047	1043	1000	1063	1087	1067	1067
suspended solids, mg/L	150	602	1003	1734	4011	-	-	-	-

Note(s):* iron (2)—value for the filtered sample.

In the second stage, analogous tests were carried out for wastewater collected after biological treatment. The results of laboratory analyses are presented in Table 4.

Table 4. Laboratory results of wastewater samples collected after biological treatment with WTS added.

Parameter	Control Sample	Contact Time—30 min Volume of WTS Added				Contact Time—60 min Volume of WTS Added			
		5 mL	10 mL	20 mL	50 mL	5 mL	10 mL	20 mL	50 mL
WTS collected on 14 September 2022; WTS moisture content—94.4%; ash content—63.76%									
phosphate, mg/L	9.89	5.67	3.28	1.39	0.38	4.79	2.46	0.82	0.25
iron, mg/L	0.51	4.12	9.17	24.11	71.15	5.17	13.05	24.11	80.56
iron(2) *, mg/L	0.38	0.47	0.47	0.47	0.68	0.45	0.45	0.66	0.71
aluminum, mg/L	0.18	13.75	35.15	41.25	46.00	26.20	39.85	44.35	46.90
dry residue, mg/L	1073	1100	1100	1100	1100	1113	1073	1120	1106
suspended solids, mg/L	18.2	446	863	1433	3524	-	-	-	-

Note(s):* iron (2)—value for the filtered sample.

Table 5 shows the efficiency of the phosphorus removal from wastewater in the tested samples, calculated from Equation (1).

$$\eta = \frac{(c_1 - c_n)}{c_1} \cdot 100\% \quad (1)$$

where c_1 is the phosphorus concentration in sample no. 1 (control) and c_n is the phosphorus concentration in the sample with sludge no. “n” after 30 or 60 min of contact.

Table 5. Phosphorus removal efficiency.

Date of WTS Collection	Contact Time—30 min Volume of WTS Added				Contact Time—60 min Volume of WTS Added			
	5 mL	10 mL	20 mL	50 mL	5 mL	10 mL	20 mL	50 mL
wastewater samples after the sand trap								
26 August 2022		43.2%	64.2%	86.9%		49.4%	68.2%	90.4%
31 August 2022	40.1%	48.6%	79.6%	90.2%	32.4%	53.5%	76.1%	91.5%
2 September 2022	31.0%	54.4%	75.5%	94.6%	32.0%	55.4%	76.6%	94.6%
average	35.5%	48.7%	73.1%	90.6%	32.3%	52.8%	73.6%	92.1%
wastewater samples after biological treatment								
2 September 2022	42.7%	66.8%	85.9%	96.2%	51.6%	75.1%	91.7%	97.5%

The results show that the addition of WTS to wastewater reduced the concentration of phosphate and the efficiency of phosphate removal at a properly selected dose was more than 90%, confirming the results obtained in earlier studies (Table 6). The amount of WTS added to wastewater had the greatest effect on phosphate removal efficiency, while contact time had a lesser effect. The highest phosphate removal efficiencies were recorded in the test samples with the addition of 50 mL of WTS with a contact time of 60 min, which were 92.1% (on average) for wastewater collected after the sand trap and 97.5% for wastewater after the biological treatment (Table 5).

Table 6. Comparison of phosphorus removal efficiency under different experimental conditions.

Removal Efficiency	P-Concentration, mg/L		Test Conditions	Reference
	Initial	Final		
86.9–94.6%	8.95–11.59	0.25–1.45	naturally dried WTS added to wastewater from WWTP, batch jar test	this study
>90%	30	<1.0	air-dried alum sludge mixed with synthetic P, batch column	[18]
up to 85%	10	not specified	oven-dried alum sludge, synthetic P and wastewater, continuous column	[41]
90%	not specified		dewatered WTS and condensed phosphate, batch column	[42]

After analyzing the dynamics of changes in the phosphate concentration as a function of WTS dose, it can be seen that it is exponential in nature, and the phosphate concentration initially decreased rapidly as the sludge dose increased from 5 to 20 mL/L of wastewater, and it can be predicted that an increase in the sludge dose above 50 mL/L would not cause a significant decrease in phosphate concentration in wastewater (Figure 5). Also, increasing the contact time increased the phosphate removal efficiency by 1.3–8.9%. The effect of contact time could be observed mainly at the lowest sludge doses, while at the highest sludge dose (50 mL), the difference was only 1.3–1.5% in favor of longer contact time.

Comparing the effect of phosphate removal from wastewater depending on the location of wastewater samples, slightly better results were observed for wastewater after biological treatment, with a difference of 5.4–5.6% in favor of these wastewater samples.

A significant increase in iron and aluminum content was also observed in test samples, which is undoubtedly related to the high content of aluminum and iron oxides in the WTS. These compounds were mainly present in suspended form. Therefore, it can be assumed that they would be removed from wastewater by sedimentation and filtration processes. This is confirmed by the low iron content in the filtered samples (iron(2) in Tables 3 and 4).

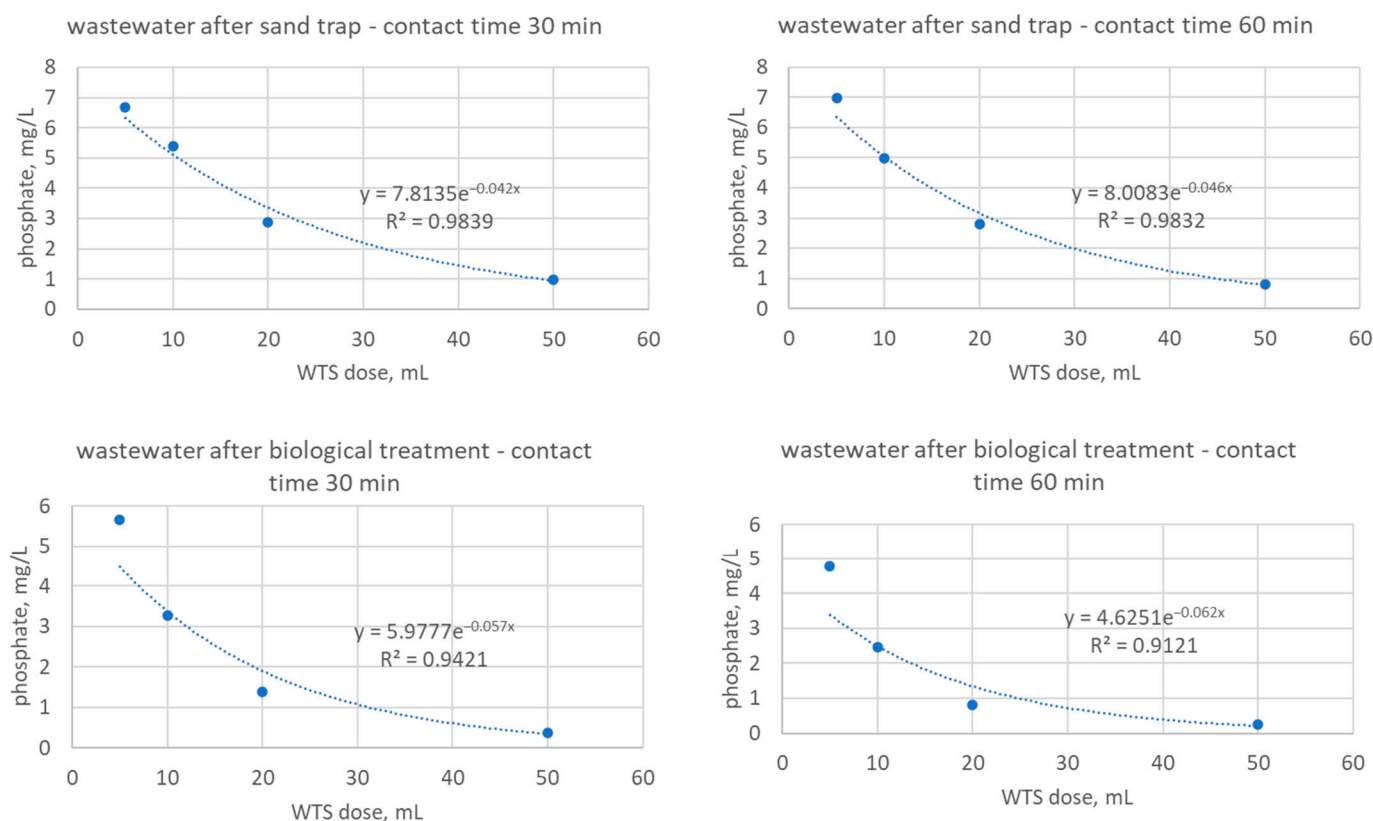


Figure 5. Dependence of the final concentration of phosphate on the sludge dose for different conditions of the experiment.

Taking into account the practical aspects of using WTS at the Astana WWTP, the demand for WTS as a reagent for removing phosphorus was also determined. Assuming a dosage of 50 mL/L and an average daily capacity of Astana WWTP of 253,216 m³/d, the daily demand for WTS would be 12,660.8 m³/d. The daily amount of WTS generated in the Astana WTP is 4651 m³/d, so the sludge could cover approx. 37% of the coagulant requirement for phosphorus removal. In the specific case of Astana, the wastewater treatment plant uses more than 1700 tons of commercial coagulant per year for phosphorus removal at a cost of approximately EUR 1.3 million/year. Replacing the commercial coagulant with WTS would save approximately EUR 480,000 per year.

4. Conclusions

The possibility of removing phosphate in WWTPs by adding sludge generated in a water treatment plant was investigated using the example of water and wastewater treatment facilities in the city of Astana. The chemical and mineral compositions of the sludge from the WTP in Astana, especially the content of aluminum oxide (from 10.8 to 14.6%) and iron oxide (from 4.58 to 5.31%), indicate the possibility of using this sludge as a reagent for phosphate removal, which was confirmed by laboratory tests. After analyzing the results of these studies, it can be concluded that the best solution from the practical

point of view is to add sludge at the initial stage of treatment (before the primary settling tanks). The sludge dose of 50 mL/L of wastewater and 60 min of contact, determined experimentally for the studied facility, makes it possible to achieve the required phosphate removal efficiency (92.1% on average). Such a solution is, on the one hand, in line with the principles of sustainable development and circular economy and, on the other hand, able to bring significant economic benefits. It should be stated, however, that increasing the WTS dose or contact time leads to an increase in phosphorus removal efficiency from wastewater, which may be a necessary treatment for sludge with different characteristics or wastewater of different composition.

As a result of experimental laboratory tests, it was also found that the addition of WTS to the wastewater at WWTP increases the concentration of iron, aluminum, suspended solids, and dry matter because of the contents of these elements in the WTS. However, this should not affect the operation of the WWTP and the quality of the treated wastewater because the above-mentioned elements are mainly present in the form of insoluble suspended solids, which are removed in the primary and secondary settling tanks, as well as in other devices such as flotation filters in the case of the Astana WWTP under study.

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