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Towards a Cleaner Textile Industry: Using ASEC to Decrease the Water Footprint to Zero Liquid Discharge

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Abstract: Textile manufacturing is the second most polluting industry. It involves a series of processes that require large amounts of water and generates highly polluting wastewater. Four liquid wastes collected at different steps from two different textile factories (synthetic and natural fibers) were treated using a new disruptive technology (Adiabatic Sonic Evaporation and Crystallization—ASEC). After the treatment of the contaminated fluids, the byproducts obtained (freshwater and crystallized solids <1% humidity) were characterized to determine depuration efficiency and their potential commercial reuse. The physicochemical parameters were analyzed in the liquid and solid phases. The results evidence a completely efficient separation of the contaminants and solutes from the liquids analyzed, resulting in 100% pure water with the characteristics of distilled water (an electrical conductivity below 20 $\mu\text{S}/\text{cm}$) suitable for other industrial processes or water reuses, including human consumption. This implies an estimated annual reduction in the water consumption of these factories of between 16 and 103 Olympic pools. It would also avoid the disposal of 181 and 966 ton/y dried residue by the current synthetic and natural fiber textile processing factories, respectively. More than 75% of the resulting solid residue was S from the synthetic fiber industry, and light elements from the natural fiber residues. The installation of ASEC technology in different phases or at the end of industrial textile processing lines could change the paradigm of water consumption to a minimum, thus reducing consumption and resulting in the complete recycling of water. Using renewable energy and residual heat transforms the system into a zero-pollution technology; it makes it possible to attain almost 0% CO₂ emissions, fulfilling the European Green Deal objectives such as a circular economy, the decarbonization of the textile industry, the protection of the biodiversity of river basins, and zero pollution.

Keywords: crystallized solids; adiabatic sonic evaporation and crystallization; water treatment; sustainable textile manufacture; circular economy



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1. Introduction

The textile industry is one of the oldest, most developed, but most polluting industries [1] in terms of chemicals, water, energy, and the waste decomposer cycle [2]; and it has doubled in the last 20 years [3]. The textile and fashion industries are considered the second most highly polluting industries after the oil industry [4,5], with an environmental footprint that goes from the cultivation of the raw materials and fabric manufacturing to the landfill disposal of consumer items [6]. It is responsible for 10% of human carbon emissions and is the second largest consumer of the world's water supply [7]. Further, Ref. [8] has estimated that the fashion industry will comprise up to 25% of the world's carbon budget by 2050. In the production and treatment of natural textile fibers (Nf: alpaca, coconut, wool, cotton, etc.) and synthetic fibers (Sf: nylon/polyester, viscose, spandex, acrylic, etc.), a series of

industrial processes are involved that require large amounts of water, generating a huge amount of highly polluting wastewater, which causes significant environmental damage. For example, manufacturing a cotton shirt requires 2700 L of water, and it takes 200 years to decompose [5]. A garment factory processing 8000 kg of cloth a day consumes around 1.6 million L of water (16% is consumed in dyeing, 8% in printing) [9]. The chemical dyeing and finishing processes employ more than 8000 chemicals [9]. The effluent is collectively highly toxic due to the sulfur, naphthol, phthalates, formaldehyde, dimethyl-fumarate (DMF), vat dyes, nitrate, acetic acid, soap, chromium (VI) and nickel compounds, and metals (e.g., Cd, Hg, Ni, Cu, As, Co, and Pb), among others [10,11]. Formaldehyde-based coloring agents, hydrocarbon-based softeners, and non-biodegradable coloring chemicals may be other dangerous chemicals present in the wastewater. Many colorants produce carcinogenic effects due to chlorine [9]. Even some organic textile dyes may cause adverse effects in the form of environmental pollution [12,13]. Sodium hydroxide is used in Nf for dye penetration (“scouring”), and soaps and alkaline solutions are used to remove grease and impurities [14]. Some chemicals are employed to make the textiles more resistant to water, stains, wrinkles, bacteria, or molds [10]. Some other pollutants also originate from the textile industry; i.e., Nf processing implies the release of phytosanitary products [14], and Sf releases a significant quantity of microplastics into the environment [3,15]. In summary, Ref. [14] evaluated the processes used to produce natural and synthetic fibers and their potential environmental impacts, and determined that the issues concerning usage were, primarily, the quality and nature of the chemicals used for laundering or dry cleaning during the products’ lifetime, and other issues relating to disposal.

In Europe, the water from textile processing is normally mixed with domestic urban wastewater residue, and after depuration it is dumped into river basins. According to the European regulations of the Waste Framework Directive 2018/851 [16], by January 2025, each member state should have set up a separate mode of collection for the textile sector, and waste management plans should include the prevention of waste generation. One of the target objectives of the Waste Directive by 2025 is that the preparation for the re-use and recycling of municipal waste should be increased to a minimum of 55% by weight. Therefore, the minimization of contaminants in water is an essential aspect for its re-use and recycling.

Water scarcity, contamination, and the unequal distribution of drinking water are worldwide problems. The aim of the United Nations Sustainable Development Goal 6 is to ensure the availability and sustainable management of sanitation and water for all; therefore, the proper management and exploitation of water resources are urgently required. The objectives of the European Green Deal also include water and the protection of biodiversity in aquatic ecosystems as priority objectives [17]. So, some technologies, such as desalination plants or wastewater treatment plants, are used to obtain water from primary resources, or are depurated; however, they are not completely efficient in recovery [17]. Furthermore, the secondary residues obtained from depuration require costly waste management plans due to the high volumes and their dangerousness (unstable compounds in the aquatic environment). Some byproducts derived from water treatment (sludge), and used as fertilizers, can reach aquifers and rivers, causing pollution, diseases, and adverse effects on the structure of the food supply for water fauna [18]. Although the aim of Directive 2010/75/EU [19] is to prevent pollution and has regulations that apply to industrial installations, they do not apply to diffuse sources of pollution [18].

Nevertheless, an innovative and disruptive technology based on evaporation and crystallization processes conducted in one step under adiabatic conditions and forcing a sonic acceleration of the contaminated fluid was designed for a total recovery of water from liquid residue, obtaining freshwater and crystallized solids as useful byproducts [20]. This process is called Adiabatic Sonic Evaporation and Crystallization (ASEC), which can completely separate water from particulates and dissolved solids. Recently, in [20], the technology was tested with mining residues and showed a 100% efficiency (as distilled water), obtaining valuable crystallized solids for raw material recovery.

This is the first time that depuration technology has been used on samples from liquid textile industry waste, and that the by-products obtained have been characterized. The aim of the current study was to evaluate the efficiency of this active treatment system with regard to the waste from the textile industry. Four samples of industrial liquid waste from two different textile factories and their processes were treated, and the byproducts obtained (pure water and crystallized solids) were characterized. The environmental impact is considered and an economic approach to the revalorized byproducts is presented.

2. Materials and Methods

2.1. Liquid Residues Samples

The scheme of the industrial processes for both synthetic fibers (Sf) and natural fibers (Nf) comprises a series of phases (partially cyclical) that are summarized in Figure 1. For the Sf, different amounts of water at different temperatures are used in baths with glues, detergents, dyes, fixatives, etc. These compounds will be in solution in the output effluent, with a total average volume of 150 m³ used in the industrial process per day. These volumes of liquid waste from the factory are treated at the wastewater treatment plant (WWTP).

Aliquots of three different liquid residue samples were collected from the different phases of the Sf textile processing line (Figure 1a). Sample S1 was water from the preparation phases of the autoclaves. The second sample (S2) was collected from the staining and dyeing phases called jiggers that also contained fluid from the previous treatment. Finally, sample S3 was the effluent from the two previous phases plus residual water sewage from the different facilities of the textile factory collected before going to the WWTP.

In the case of the manufacture of Nf textiles, some of the processes were different (Figure 1b), but they also employed chemicals and treatments (dispersants, surfactants, colorants, etc.). Different dumping pipelines were connected to the WWTP. The fourth sample was collected from the Nf textile manufacturer after all the treatments and together with domestic wastewater before the WWTP (homologous to S3). The daily volume of water consumed by this factory is 950 m³.

2.2. ASEC Technology

The disruptive technology Adiabatic Sonic Evaporation and crystallization (ASEC) was designed (World International Patent Organization: EP3135635) to purify contaminated fluid using a physical approach without the use of chemicals. This occurs by distillation, which results in separate particulate and dissolved solids and liquids based on adiabatic changes and the acceleration of the contaminated fluid to be treated (Figure 2). The results are distilled water and crystallized solid salts. The ASEC process mainly consumes heat instead of electricity. Also, ASEC may use residual heat from the polluting industry, and/or conventional fuel-based energies, and/or classical electricity from the grid. The ASEC process consumes 3–5 kWh/m³ of treated fluid when using renewable energy sources (<1 kWh when using residual heat). The necessary energy may also be produced by renewable energies, such as thermal–solar, photovoltaic panels, etc., or even residual heat originating from other industrial processes [20], which may result in almost 0% of CO₂ emissions [21]. Such complete decarbonization of the textile industry, the protection of biodiversity, and zero pollution are among the objectives and goals of the European Green Deal and the U.N.'s Sustainable Development.

Four samples from different processes and factories (S and N) were treated using the ASEC process to verify the efficiency of the technology with liquid waste from different textiles. Therefore, 50 L of each sample of the industrial waste collected from the manufacturing processes (Figure 1) were treated with the ASEC technology (Figure 2). After the treatment of these fluids using ASEC, a total volume of 50 L of clean water S1_{out} was collected, along with a total weight of about 950 g of crystallized solids; a volume of 50 L of clean water S2_{out} and 260 g of crystallized solids were collected after treatment; and finally, around 50 L of distilled water from S3_{out} and 350 g of crystallized solids were collected from the synthetic fiber manufacturing samples. Also, 50 L from the Nf (N_{in}) factory was treated

and the byproducts (N_{out}) obtained were 50 L of pure water and 200 g of crystallized solids. In all these cases, the percentage of humidity of the crystallized solids was lower than 1.

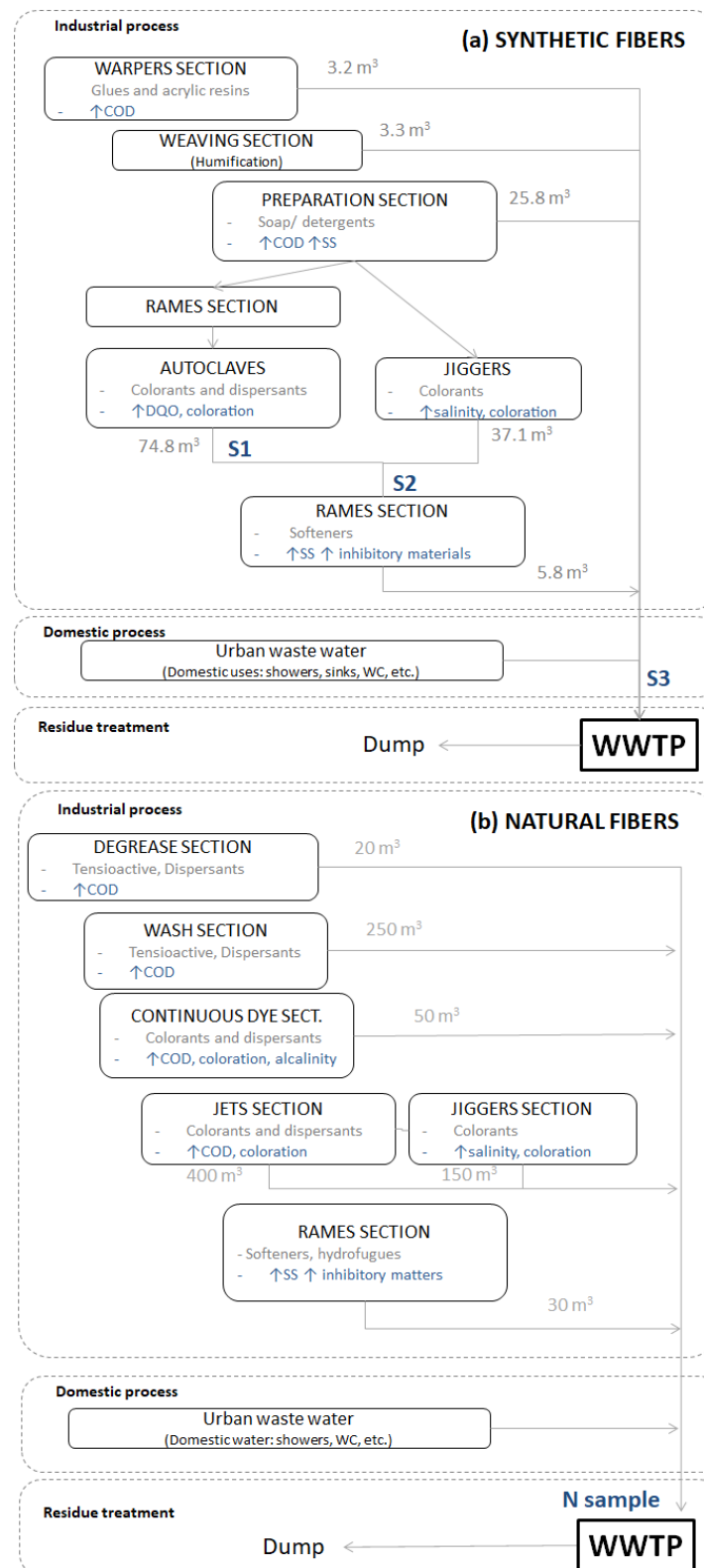


Figure 1. (a) Schemes of the synthetic (Sf) and (b) natural fiber (Nf) textile manufacturing processes and the sampling points in the manufacturing processes (S1, S2 and S3 for synthetic fibers and Nf for natural fibers).

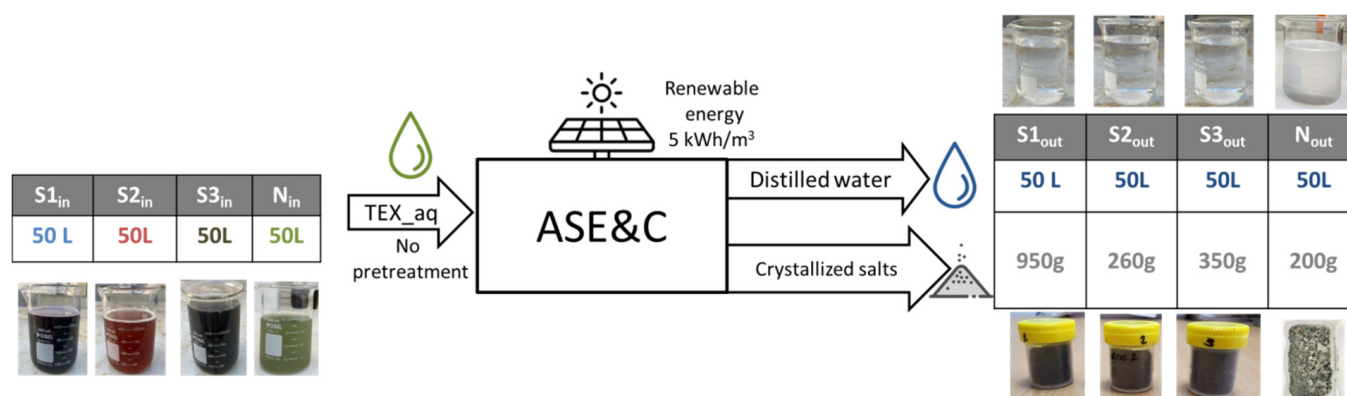


Figure 2. ASEC design global working scheme, the mass balance and pictures of synthetic (S) and natural (N) fiber manufacturing samples before (-_{in}) and after the treatment (-_{out}).

2.3. Sample Collection and Analyses

Samples of liquid industrial waste (S1_{in}, S2_{in}, S3_{in}, N_{in}) were collected directly in 1 L amber bottles from the industrial plants, according to Figure 1. Also, 500 mL aliquots of the output liquids (S1_{out}, S2_{out}, S3_{out}, N_{out}) were collected after the ASEC treatment and acidified (1 μL HNO₃/mL), and then the elements were analyzed. The concentrations of the elements were determined using an Inductively Coupled Plasma–Mass Spectroscopy (ICP-MS, ICAP-Q, Thermo-Fisher Scientific, Bremen, Germany).

Solid crystalized salt samples were collected with a Teflon spoon and stored in plastic tubes. The samples were characterized using a Vanta™ Handheld (Olympus Scientific Solutions, Waltham, USA) XRF portable analyzer (detection limits: <5 ppm for Mn, Fe, Co, Ni, Zn, Rb, Sr, Nb, Th, Se, Sb; <10 ppm for Cu; <25 ppm for Ca and K; <50 ppm for S and P; <400 ppm Al and Si). Some light elements were presented as a total (H, He, Li, Be, B, C, N, O, F, Ne, Na) [22].

Quality assurance and quality control (QA/QC) were followed by use of certified protocols and laboratories, as detailed in [20].

3. Results and Discussion

3.1. Mass Balance

The volumes of the liquids used as the input of the ASEC processes were completely recovered after the treatments. Volumes of 50 L were supplied to the ASEC equipment, and 50 L of each completely transparent sample was recovered after the treatment (Figure 2) with ~10 mg/L of suspended solids; the pH ranged between 6.87 and 7.01, and the electrical conductivity was 16 μS/cm (Table 1). The crystalized dissolved elements from S1, S2, and S3 had masses of 950, 260, and 350 g, respectively; in other words, a production of 19 g of conglomerates was yielded per liter of S1, while 5.8 g/L was yielded for S2, and 7 g/L for S3. Finally, 4 g of dried solids were obtained per liter of sample.

Table 1. Physicochemical analysis results for the untreated (S1_{in}, S2_{in}, S3_{in}, N_{in}) and the treated fluids (S1_{out}, S2_{out}, S3_{out}, N_{out}) using the ASEC technology.

		Input				Output			
	Units	S1 _{in}	S2 _{in}	S3 _{in}	N _{in}	S1 _{out}	S2 _{out}	S3 _{out}	N _{out}
EC	μS/cm	11,390	2000	2660	6670	16.2	16.7	16.3	38.1
T	°C	24.3	24.4	23.9	25.4	24.7	24.4	25.1	25.3
pH		6.66	8.99	7.43	7.27	6.87	6.80	7.01	6.53
COD	mg/L _{O2}	8950	3069	3960	6900	<10	<10	<10	<10
TSS	mg/L	7170	2000	2660	4200	10.2	10.5	10.3	9.99
Chlorides	meq/L	56.13	9.86	13.11	18.31	0.08	0.08	0.08	0.06

Table 1. Cont.

	Units	Input				Output			
		S1 _{in}	S2 _{in}	S3 _{in}	N _{in}	S1 _{out}	S2 _{out}	S3 _{out}	N _{out}
Sulphates	mg/L	~8000	200	~400	>200	<25	<25	<25	<25
Elements									
Al	µg/L	801	8063	4023	117	n.d.	n.d.	n.d.	n.d.
Cd	µg/L	7.80	n.d	n.d	0.2	n.d.	n.d.	n.d.	n.d.
Ca	mg/L	1999	1463	1035	10.9	n.d.	n.d.	n.d.	n.d.
Co	µg/L	154	14.2	169	3.2	n.d.	n.d.	n.d.	n.d.
Cu	µg/L	763	241	735	197	n.d.	n.d.	n.d.	n.d.
Cr	µg/L	23.4	7.00	17.2	110	n.d.	n.d.	n.d.	n.d.
Mg	µg/L	4152	1562	2966	40,842	<5	n.d.	<5	<5
Na	mg/L	4179	702	4177	1951	<5	<5	<5	<5
Zn	µg/L	13,833	258	1242	75	<20	<20	<20	n.d.
Li	µg/L	14.6	125	192	44.4	n.d.	n.d.	n.d.	n.d.
K	mg/L	12.5	11.4	7.78	92.6	<0.1	<0.1	<0.1	<0.1
Fe	µg/L	370	1057	418	88.9	n.d.	n.d.	n.d.	n.d.
Ni	µg/L	419	10.6	11.0	3.2	n.d.	n.d.	n.d.	n.d.
As	µg/L	0.75	1.54	6.33	3.60	n.d.	n.d.	n.d.	n.d.
Sr	µg/L	33.5	18.7	92.4	803	n.d.	n.d.	n.d.	n.d.
Y	µg/L	14.1	37.3	138	3.00	n.d.	n.d.	n.d.	n.d.
Cs	µg/L	36.4	90.0	162	0.26	n.d.	n.d.	n.d.	n.d.
Ba	µg/L	6.84	17.8	22.4	99.5	n.d.	n.d.	n.d.	n.d.
La	µg/L	41.4	47.4	51.3	0.19	n.d.	n.d.	n.d.	n.d.
Ce	µg/L	81.7	47.2	87.1	n.d	n.d.	n.d.	n.d.	n.d.
Pr	µg/L	13.1	12.1	15.3	0.10	n.d.	n.d.	n.d.	n.d.
Nd	µg/L	66.6	60.2	101	0.20	n.d.	n.d.	n.d.	n.d.
Sm	µg/L	8.58	14.6	5.55	0.10	n.d.	n.d.	n.d.	n.d.
Gd	µg/L	4.73	20.0	3.41	0.56	n.d.	n.d.	n.d.	n.d.
Dy	µg/L	9.80	37.7	5.15	0.10	n.d.	n.d.	n.d.	n.d.
Er	µg/L	16.3	20.4	2.71	0.10	n.d.	n.d.	n.d.	n.d.
Yb	µg/L	14.1	30.1	23.1	0.46	n.d.	n.d.	n.d.	n.d.
Pb	µg/L	2.14	6.44	5.75	0.15	n.d.	n.d.	n.d.	n.d.

Note: n.d.: not detected.

3.2. Results of the Characterization of the Fluids

The physicochemical parameters of the fluids before and after the treatment are summarized in Table 1. The electrical conductivity (EC) values of the Sf textile liquid waste samples were 11,390, 2000, and 2660 µS/cm for S1, S2, and S3, respectively, but reached the common values of distilled water, lower than 20 µS/cm (16.4 ± 0.2 µS/cm) in all the output samples. The pH was slightly neutralized from 6.66–8.99 to 6.87–7.01 for each of the samples. The values of total suspended solids (TSS) in the incoming effluent from the different steps were 8950 mg/L in S1, 2000 mg/L in S2, and 2660 mg/L in S3, but these were reduced to lower than 10 mg/L after the ASEC treatment. The Cl concentration decreased from 56, 9, and 13 meq/L (for S1, S2, and S3, respectively) to 0.08 meq/L in the output liquid. The reduction in the chemical oxygen demand (COD) after treatment reached the value of 10 mg/L O₂. Regarding the concentrations of the metals, complete removal was observed for most of the elements (Cd, Ca, Co, Cu, Cr, and Zn), while others considerably reduced their concentrations. For example, Al registered concentrations between 737 and 4023 µg/L from the input and between 7 and 29 µg/L from the output samples; Mg and Na reduced their concentrations by two orders of magnitude in the treated liquid. In short, the output fluids had the characteristics of distilled water.

The physicochemical parameters of the Nf samples showed the same trend. The EC was reduced from 6670 to 38 µS/cm, the pH was modified from 7.27 to 6.53, and the TSS, chlorides, and sulfates were completely removed in the output water.

3.3. Composition of the Crystallized Solids

The solid crystallized conglomerates collected from the output of the ASEC were characterized chemically (Figure 3). A total of 950 g of crystallized solids collected in S1 were almost 99% S ($5879 \pm 0.098\%$), with a probable origin in the surfactants. The crystallized solids from S2 were composed of 71% S (27,800 ppm), followed by Si at 19% (7220 ppm), while 8% was K and Ca in equal measures, and 2% was a cocktail of different elements, such as Fe (1%), Cu, Rb and Co, among others. The composition of the solids in S3 was more heterogeneous: there was 46% S (27,800 ppm), 19% Mg, 19% Al, 8% Si, and 8% other elements, including 3% Ca, 2% P, and others in proportions below 1% (K, Fe, Zn, Cu, Sb, etc.).

Almost three-quarters of the crystallized solids in the solid residue of Nf were light elements [20], comprising 734 g/kg. Magnesium salts made up 8% of the total composition, followed by S (7%).

The estimated crystallized loads recovered from a yearlong ASEC treatment of fluid residues are summarized in Table 2. Using the ASEC process, around 5187 tons of solid residues could be retained from S1, 2370 tons from S2, and 3833 tons from S3, but a greater amount of annual solid residues would be recovered from the natural fiber factory (13,870 tons) than from the synthetic fiber one. The variability and heterogeneity in the compositions of the Sf samples were determined by dilution in the different outlets (Figure 1). For a closer comparison between both factories, the use of last sampling points (S3 for Sf, and N for Nf) would be appropriate; however, the Nf factory uses higher volumes of water than the Sf one. Therefore, in this case, the Nf factory would generate 3.6 times more solid residues than Sf. Due to the high heterogeneity of the salts formed and the inability to recover the elements contained in the solids, together with the presence of impurities in the materials, the best management strategy would be disposal in sanitary deposits. However, the ASEC process would produce a smaller disposal volume than the usual treatment technologies, and therefore represents an easier and cheaper way to manage such waste.

A previous study [23] demonstrated a recovery rate of 77% of water and 66% of NaCl from a briny textile solution using reverse osmosis (RO).

Table 2. The yearly metal load estimated for the different conglomerate salts collected for the different fluids.

		S1	S2	S3	N
S	ton	304,966	66	181	963
Si	ton	17.5	17.1	32.3	531
Ca	ton	5.5	3.4	10.8	416
K	ton		3.6	5.5	371
Mg	ton			76	1080
Al	ton			75	251
P	ton				43
Sb	ton				5.5
ΣLight elements	ton				10,194
Co	kg	363	149	123	
Cu	kg	638	265	728	4771
Fe	kg	555	497	2070	3336
Mo	kg	166	69	77	
Nb	kg	93	33	31	
Ni	kg	223	121	77	
Rb	kg	1048	194	506	506
Se	kg	62	31	23	
Sr	kg	52	28	73	2725
Zn	kg	8746	1007	1805	1616
Th	kg	285		84	
Mn	kg			330	

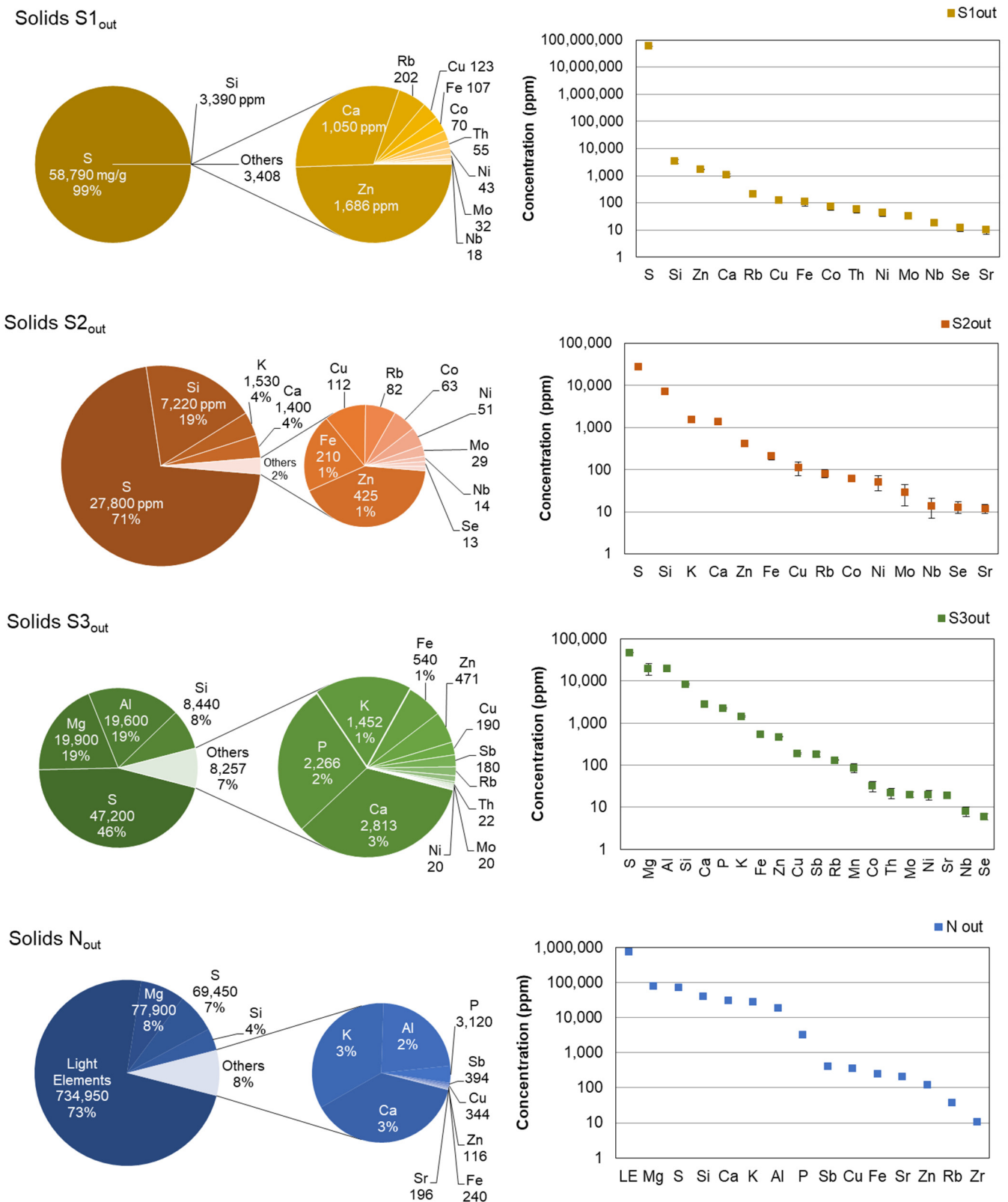


Figure 3. Composition of elements in percentages (%), **left**) and concentrations (ppm, on the logarithmic scale, **right**) of the crystallized solids collected using the ASEC technology for the synthetic (S1_{out}, S2_{out}, S3_{out}) and natural fibers samples treated (LE: light elements).

3.4. Revalorization

Previously mentioned authors [6,24,25] stated that the industrial waste generated from manufacturing processes is a potentially enormous source of secondary raw material, which is not used at present even though it could be reintroduced onto the market. Regarding the reuse of water, Ref. [26] has pointed out that water treatment in the textile industry could lead to a reduction of more than 40% in the consumption of freshwater, while the use of the ASEC technology has demonstrated an improvement of up to 100%. Therefore, water with a low mineral content resulting from such treatment could be reused in similar manufacturing processes or other industrial processes, or for agriculture, etc. It could even be safely returned to rivers as a potential measure to restore river basins. The use of the ASEC technology, coupled with the pre-existing systems in these two factories, would annually save the equivalent of 103 Olympic swimming pools for the Nf factory, and 16 for the Sf factory.

Additionally, the resulting crystallized solids could play an important role in the supply of raw materials. Based on the market prices of elements [27–29], an estimation of the potential value of the metals recovered is around \$ 62 thousand per year for the Sf factory and USD 275 thousand for the Nf factory (Table 3). The element most considered in this estimation is sulfur. Sulfur represented 99, 71 and 46% of the crystallized solids resulting from the treated Sf samples (Figure 3). According to the market overview of 2023 [30], the latest sulfur prices oscillated between USD 169/ton on the European market, and USD 252/ton on the North American market, with intermediate prices on the Asian market. Therefore, the ASEC system coupled to S1 would remove 305 thousand tons of S yearly, which means an economic revalorization of USD 76 million for sulfur extraction from such solid waste (Table 3). In contrast, the solid sample from the Nf factory was composed of 73% of light elements, followed by Mg (8%), and S represented 7% of the total composition (Figure 3). So, sulfur represents a potential economic recovery of USD 243 thousand per year for the Nf industry. However, these estimations are only calculated roughly, and the recovery of elements from these wastes might not be profitable due to the high heterogeneity of the samples; however, the expenses of the metallurgical process of selection, the extraction of elements, and other logistical expenses are not taken into consideration in the calculation of the potential value in this article. But the greatest milestone that deserves to be highlighted in this process is the significant savings in water for both factories, and the condensation of their contaminants, which means that they could be stored and managed more easily and cheaply. Annual recoveries of water and salt from textile RO treatment lead to estimated cost savings regarding water and salt of USD 176,256 and USD 37,000, respectively [23].

Table 3. Estimated potential valuation (in USD/year) of the elements of economic interest contained in the crystallized solids obtained using the ASEC technology for the synthetic factory (S1, S2, S3) and natural fiber textile factory (N).

	S1	S2	S3	N
S	76,851	16,596	45,585	242,744
Co	10,893	4477	3679	-
Cu	3828	1592	4369	28,628
Mo	4316	1786	1993	-
Nb	5033	1788	1653	-
Ni	2877	1559	989	-
Se	1152	570	425	-
Zn	17,492	2014	3610	3232
Total	76,897,041	30,380	62,303	274,604

The management of hazardous waste includes the collection, recycling, treatment, transportation, disposal, and monitoring of waste disposal sites [31]. Given the new solid state of these chemicals as crystallized salts, the waste processing of such conglomerates could be improved. Chemical separation techniques could be used to sort them into different material fractions for recycling, or pre-sorted waste elements could be processed into secondary raw materials. New (raw) materials might be obtained. Through incineration, the volume could be reduced or energy recovered (anaerobic digestion of organic elements), or this could even be achieved through pyrolysis. In any case, the compaction and reduction in volume leads to a lowering of the expenses for transportation and disposal.

Nanotechnology (nanoparticles, nanocomposites, nanotubes, etc.) look promising in terms of water treatment and recovery in the global textile industry [32]. Some other wastewater depuration strategies in the textile industry are based on the use of the ultrasonic assisted co-precipitation method and nanoparticles, with successful results regarding COD, surfactants, color, and turbidity reduction [33]. Dye solutions might also be removed by strong oxidant species electro-generated on diamond electrodes [34]. We might even use phytoremediation, applied to blended wastewater from the textile industry [35]. *Lemna minor* is able to reduce COD [36], *Lemna gibba* L. removes organic dyes [37], and some terrestrial plants can absorb the dyes accumulated in soils [38]. Also, a combined treatment of ultrafiltration and bioremediation has been proven able to remove coloration and reduce the COD [39].

Although these methods and techniques can reach a specific efficiency and thus attain the legal requirements of textile discharges, they are costly, and the residue generated is not economically viable for commerce, while only a few studies consider the reuse of contaminants (e.g., dyes [40]) and water [23]. Also, there are certain emerging pollutants with serious environmental impacts, such as microplastics [41], which are not considered by many depuration processes, so these pollutants are simply dumped into rivers, soils, and ultimately oceans.

3.5. European Critical Raw Materials and European Green Deals

Nowadays, the needs for materials in industries such as the automotive, construction, or chemical in Europe are affected by the demand–supply disruption [42]. The critical raw materials (CRM) have been listed by the European Commission in relation to their economic importance and the supply risk they represent to the EU. CRM are irreplaceable in high-tech products and emerging innovations (solar panels, wind turbines, electric vehicles, etc.), so they play a significant role concerning climate change, and the protection of the environment [43]. The EU elaborated a list of these 14 CRM in 2010 that has been increased to the 34 CRM of today; among them are metals, metalloids and minerals (As, Si, Li, Sb, Be, Bi, Cu, Ga, Ge, Ni, Nb, Sc, Tl, Sr, P, bauxite, feldspar, phosphate rock, natural graphite, etc.) and rare earth elements (heavy and light) [44,45]. Apart from the significant importance of these materials for manufacturing, they also play an important role in the transition toward green technologies, e.g., Nb and Tm are fundamental to reaction engines. China dominates the market for most of the CRMs, and together with Russia, they are the main suppliers of CRMs to Europe [46], but Europe also has reserves of some of these materials, such as Sr, In, Hf, Ga, Si and Ge.

The latest European CRM Act [45] received much criticism for promoting mining extraction. So, the re-exploitation of residues, such as those coming from the textile industry and other industrial wastes, as a source of CRM would be a sustainable choice to secure their supply. It is known that some elements may be recycled with promising recycling rates, such as W (42%), Eu (38%), I (32%) or Sb, Pa and Rh (28%) [44]. The Commission published a report highlighting the potential for a more circular usage of CRMs in the economy [17,43]. Important quantities of different elements were found in the crystallized solids originating from the different samples (Table 2) that might be employed in the construction or chemical industries (305 thousand ton/y of S, 1000 ton/y of Mg, 531 ton/y

of Si, etc.), or as trace elements commonly used as catalyzers with greater value (363 kg/y Co, 4300 kg/y Mo, 1000 kg/y Rb).

There is also a need to be aligned with the EU's climate goals [19], which demand an entirely new perspective on waste as a sustainable source of materials, which is commonly known as the circular strategy [47,48]. Waste reprocessing helps to prevent valuable materials from ending up in landfills by transforming them into secondary raw materials; this means a reduction in the planetary water and carbon footprint. Therefore, is applied to the textile sector, the ASEC technology would cover the following demands of the EU green deals: (i) the demand for green change globally; (ii) the goal of zero pollution for a toxic-free environment by removing contaminants from effluents, and (iii) the preservation of ecosystems and biodiversity (protecting nature), (iv) because it is environmentally friendly and, (v) it can work with clean (renewable), reliable and affordable energy, so it reduces the hydrogen and carbon footprint. Finally, it is able to transform waste into clean water and solids with a potential commercial value (circular economy).

4. Conclusions

The textile industry consumes around 215 billion L of water annually; it is responsible for 8–10% of the emissions of greenhouse gases, and it is expected to grow exponentially in the near future. Furthermore, it is considered the second most polluting industry due to its utilization of colorants, detergents, dispersants, and other residues derived from fabrics, such as microplastics. The current study shows the efficiency of a process for water recuperation in industrial processes and the avoidance of a significant impact on water bodies going from rivers to the ocean, while also contributing to a circular economy. Industrial effluents collected at synthetic and natural fiber textile factories were treated with the new ASEC technology at different steps in the process. The four liquid wastewater samples were completely separated into distilled water (available for new uses, even as drinking water) and four types of conglomerated crystallized solids (<1% humidity), with some potential commercial use after revalorization (46–100% S), especially for the element S associated with Sf factories (potential revenues of up to USD 76 million per year). In the case of Nf, water consumption, which is a much more significant milestone, represented higher recovery volumes (320,000 m³/year for this particular factory). But the revalorization of the solids was not recommended because the resulting salts were too heterogeneous (73% light elements, 8% Mg, 7% S).

For both factories, the installation of the ASEC technology could change the paradigm of water consumption to the minimum, and allow for complete water recycling (volumes of 16 and 103 Olympic pools were the annual savings). In the case of the solid residue, the resulting safety and reduction in volume would reduce expenses in waste management (annual removal of 181 and 966 ton/y of dried residue). The ASEC technology could function as a hub for the transition to efficient water use for the global textile industry. It would achieve important key milestones in these two factories: zero liquid discharges; vast reusable volumes of water, and the avoidance of the contamination of water bodies (zero contaminant discharges to the environment). These are the objectives of the European Green Deal (clean and circular economy, protection of nature, green change, and elimination of pollution) and the United Nations Sustainable Development Goals. Industries would benefit from important economic savings such as water usage, residue management, and the possibility to obtain new sustainability awards.

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References

1. Khan, S.; Malik, A. Environmental and Health Effects of Textile Industry Wastewater. In *Environmental Deterioration and Human Health*; Malik, A., Grohmann, E., Akhtar, R., Eds.; Springer: Dordrecht, The Netherlands, 2014. [CrossRef]
2. Vicaire, Y. The Greenpeace Detox Campaign. 2017. Available online: https://echa.europa.eu/documents/10162/22979590/230217_substitution_webinar_greenpeace_detox_en.pdf/fa71a525-12df-6978-dadf-2e3ed392d746 (accessed on 3 August 2023).
3. Tummino, M.L.; Varesano, A.; Copani, G.; Vineis, C. A glance at novel materials from the textile world to environmental remediation. *J. Polym. Environ.* **2023**, *31*, 2826–2854. [CrossRef]
4. Pacini, H. Seizing the Opportunities of a Circular Economy in Textiles. *UNCTAD (United Nations Conference on Trade and Development)*, 28 June 2021. Available online: <https://unctad.org/news/seizing-opportunities-circular-economy-textiles> (accessed on 24 April 2023).
5. Gupta, R.; Kushwaha, A.; Dave, D.; Mahanta, N.R. Chapter 10—Waste Management in Fashion and Textile Industry: Recent Advances and Trends, Life-Cycle Assessment, and Circular Economy. In *Emerging Trends to Approaching Zero Waste, Environmental and Social Perspectives*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 215–242. [CrossRef]
6. Shirvanimoghaddam, K.; Motamed, B.; Ramakrishna, S.; Naebe, M. Death by waste: Fashion and textile circular economy case. *Sci. Total Environ.* **2020**, *7185*, 137317. [CrossRef]
7. EPA (United States Environmental Protection Agency). Facts and Figures about Materials, Waste and Recycling: Textiles: Material-Specific Data. 2021. Available online: <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/textiles-material-specific-data> (accessed on 17 May 2021).
8. Pandey, K. Fashion Industry May Use Quarter of World's Carbon Budget by 2050. *Down to Earth*, 2018. Available online: <https://www.downtoearth.org.in/news/environment/fashion-industry-may-use-quarter-of-world-s-carbon-budget-by-2050-61183> (accessed on 24 April 2023).
9. Singa, K.; Pandit, P.; Maity, S.; Sharma, S.R. Chapter 11-Harmful environmental effects for textile chemical dyeing practice. In *Green Chemistry for Sustainable Textiles Modern Design and Approaches*; The Textile Institute Book Series; Woodhead Publishing: Sawston, UK, 2021; pp. 153–164. [CrossRef]
10. European Chemicals Agency (ECHA). Clothes and Textiles. Chemicals in Our Life. Available online: <https://chemicalsinourlife.echa.europa.eu/clothes-and-textiles> (accessed on 7 August 2023).
11. Gaonkar, O. *An Overview of Toxic Chemicals in Textiles*; Technical Report: December; Toxics Link: New Delhi, India, 2021.
12. Hassani, A.; Eghbali, P.; Ekicibil, A.; Metin, O. Monodisperse cobalt ferrite nanoparticles assembled on mesoporous graphitic carbon nitride (CoFe₂O₄/mpg-C₃N₄): A magnetically recoverable nanocomposite for the photocatalytic degradation of organic dyes. *J. Mang. Magn. Mater.* **2018**, *456*, 400–4212. [CrossRef]
13. Khataee, A.; Eghbali, P.; Irani-Nezhad, M.H.; Hassani, A. Sonochemical synthesis of WS₂ nanosheets and its application in sonocatalytic removal of organic dyes from water solution. *Ultrason. Sonochem.* **2018**, *48*, 329–339. [CrossRef]
14. Chen, H.L.; Burns, L.D. Environmental Analysis of Textile Products. *Cloth. Text. Res. J.* **2006**, *24*, 546–550. [CrossRef]
15. Carney Almroth, B.M.; Åström, L.; Roslund, S.; Petersson, H.; Johansson, M.; Persson, N.K. Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. *Environ. Sci. Pollut. Res.* **2018**, *25*, 1191–1199. [CrossRef] [PubMed]
16. S.I. No. 323/2020-European Union (Waste Directive) Regulations 2020. Available online: <https://www.irishstatutebook.ie/eli/2020/si/323/made/en/print?q=waste+directive+> (accessed on 9 August 2023).
17. European Commission. The European Green Deal. Brussels, 11.12.2019 COM (2019) 640 final. 2019. Available online: https://scholar.google.com/scholar_lookup? (accessed on 7 August 2023).
18. Sasakova, N.; Gregova, G.; Takacova, D.; Mojzisoava, J.; Papajova, I.; Venglovsky, J.; Szaboova, T.; Kovacova, S. Pollution of surface and ground water by sources related to agricultural activities. *Sec. Waste Manag. Agroecosyst.* **2018**, *2*, 42. [CrossRef]
19. EU. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control). Available online: <http://data.europa.eu/eli/dir/2010/75/oj> (accessed on 14 August 2023).
20. Bonnail, E.; Vera, S.; Blasco, J.; Conradi, M.; DelValls, T.Á. Metal Pollution and Mining in the Iberian Pyrite Belt: New Remediation Technologies to Improve the Ecosystem Services of the River Basins. *Water* **2023**, *15*, 1302. [CrossRef]

21. Switch2Green. The EU SWITCH to Green Flagship Initiative. A Gateway to Inclusive Green Economy. Available online: <https://www.switchtogreen.eu/the-eu-green-deal-promoting-a-green-notable-circular-economy/#:~:text=The%20European%20Green%20Deal%20aims,biodiversity%20loss%20and%20cut%20pollution> (accessed on 23 August 2023).
22. Portaspecs.com. Why Light Elements are Difficult to Measure with Portable XRF. Portable Spectral Services 2023. Available online: <https://www.portaspecs.com/why-light-elements-are-difficult-to-measure-with-portable-xrf/> (accessed on 23 August 2023).
23. Partal, R.; Basturk, I.; Hocaoglu, S.M.; Baban, A.; Yilmaz, E. Recovery of water and reusable salt solution from reverse osmosis brine in textile industry: A case study. *Water Res. Indus.* **2022**, *27*, 100174. [CrossRef]
24. Wang, Y. Fiber and Textile Waste Utilization. *Waste Biomass Valor.* **2010**, *1*, 135–143. [CrossRef]
25. Khan, M.M.R.; Islam, M.M. Materials and manufacturing environmental sustainability evaluation of apparel product: Knitted T-shirt case study. *Textiles Cloth. Sustain.* **2015**, *1*, 8. [CrossRef]
26. Vajnhandl, S.; Volmajer Valh, J. The status of water reuse in European textile sector. *J. Environ. Manag.* **2014**, *141*, 29–35. [CrossRef]
27. USGS (U.S. Geological Survey). *Mineral Commodity Summaries*; Report 210; U.S. Geological Survey: Reston, VA, USA, 2023. [CrossRef]
28. U.S. Geological Survey. *Mineral Commodity Summaries 2020*; U.S. Geological Survey: Reston, VA, USA, 2020.
29. León, R.; Macías, F.; Cánovas, C.R.; Pérez-López, R.; Ayora, C.; Nieto, J.M.; Olías, M. Mine waters as a secondary source of rare earth elements worldwide: The case of the Iberian Pyrite Belt. *J. Geochem. Explor.* **2021**, *224*, 106742. [CrossRef]
30. Chemanalyst. 2023. Available online: <https://www.chemanalyst.com/Pricing-data/sulphur-39> (accessed on 14 October 2023).
31. Kanagamani, K.; Geethamani, P.; Narmatha, M. Hazardous Waste Management. In *Environmental Issues and Sustainable Development*; IntechOpen: London, UK, 2021. [CrossRef]
32. Elanthendral, G.; Inbathamizh, L.; Sudha, S. Engineered Nanomaterials for Water Treatment Applications. In *Modern Nanotechnology*; Malik, J.A., Sadiq Mohamed, M.J., Eds.; Springer: Cham, Switzerland, 2023. [CrossRef]
33. Ravelo-Nieto, E.; Ovalle-Serrano, S.A.; Gutiérrez-Pineda, E.A.; Blanco-Tirado, C.; Combariza, M.Y. Textile wastewater depuration using a green cellulose based Fe₃O₄ bionanocomposite. *J. Environ. Chem. Engine.* **2023**, *11*, 109516. [CrossRef]
34. Solano, A.M.S.; de Araújo, C.K.C.; de Melo, J.V.; Peralta-Hernandez, J.M.; da Silva, D.R.; Martínez-Huitle, C.A. Decontamination of real textile industrial effluent by strong oxidant species electrogenerated on diamond electrode: Viability and disadvantages of this electrochemical technology. *Appl. Catalysis B Environ.* **2013**, *130–131*, 112–120. [CrossRef]
35. Amare, E.; Kebed, F.; Berihu, T.; Mulat, W. Field based investigation on phytoremediation potentials of *Lemna minor* and *Azolla filiculoides* in tropical, semi-arid regions: Case of Ethiopia. *Int. J. Phytoremed.* **2017**, *20*, 965–972. [CrossRef] [PubMed]
36. Hocini, I.; Khellaf, N.; Benabbas, K.; Djelal, H.; Amrane, A. Identification of the mechanism involved in the removal potential of textile pollutants by the aquatic plant *Lemna gibba* L. *J. Chem. Health Risks* **2020**, *10*, 145–153. [CrossRef]
37. Khellaf, N.; Djelal, H.; Amrane, A. An Overview of the Valorization of Aquatic Plants in Effluent Depuration through Phytoremediation Processes. *Appl. Microbiol.* **2022**, *2*, 309–318. [CrossRef]
38. Chandanshive, V.; Kadam, S.K.; Khandare, R.V.; Kurade, M.B.; Jeon, B.-H.; Jadhav, J.P.; Govindwar, S.P. In situ phytoremediation of dyes from textile wastewater using garden ornamental plants, effect on soil quality and plant growth. *Chemosphere* **2018**, *210*, 968–976. [CrossRef]
39. López-Rodríguez, D.; Micó-Vicent, B.; Jordán-Núñez, J.; Bonet-Aracil, M.; Bou-Belda, E. Uses of Nanoclays and Adsorbents for Dye Recovery: A Textile Industry Review. *Appl. Sci.* **2021**, *11*, 11422. [CrossRef]
40. Sierra-Solache, R.E.; Muro, C.; Maciel, A.; Illescas, J.; Díaz, M.C.; Carbajal-Franco, G.; Hernández, O.A. Water recovery from textile wastewater treatment by encapsulated cells of *Phanerochaete chrysosporium* and ultrafiltration system. *Biologia* **2020**, *75*, 1717–1729. [CrossRef]
41. Selonen, S.; Dolar, A.; Kokalj, A.J.; Skalar, T.; Dolcet, L.P.; Hurley, R.; van Gestel, C.A. Exploring the impacts of plastics in soil—The effects of polyester textile fibers on soil invertebrates. *Sci. Total Environ.* **2020**, *700*, 134451. [CrossRef] [PubMed]
42. Grilli, M.L.; Bellezze, T.; Gamsjäger, E.; Rinaldi, A.; Novak, P.; Balos, S.; Piticescu, R.R.; Ruello, M.L. Solutions for Critical Raw Materials under Extreme Conditions: A Review. *Materials* **2017**, *10*, 285. [CrossRef]
43. European Commission. *Report on Critical Raw Materials and the Circular Economy*; European Commission: Brussels, Belgium, 2018. [CrossRef]
44. COMISIÓN EUROPEA. Comunicación de la Comisión al Parlamento Europeo, al Consejo, al Comité Económico y Social Europeo y al Comité de las Regiones. Resiliencia de las Materias Primas Fundamentales: Trazando el Camino Hacia un Mayor Grado de Seguridad y Sostenibilidad. Brussels, 3.9.2020. COM 2020, 474 Final. Available online: <https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:52020DC0474&from=NL> (accessed on 15 June 2023).
45. European Critical Raw Materials Act. Proposal for a Regulation of the European Parliament and of the Council Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/102, COM, 2023. Available online: https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act_en#files (accessed on 15 June 2023).
46. Bourg, S.; SCRREEN Project's Partners. SCRREEN: Solutions for Critical Raw Materials—A European Expert Network. In *Extraction 2018*; Davis, B., Ed.; The Minerals, Metals & Materials Series; Springer: Cham, Switzerland, 2018. [CrossRef]

47. Directorate-General for Environment. EU Strategy for Sustainable and Circular Textiles. 2022. Brussels. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:9d2e47d1-b0f3-11ec-83e1-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed on 3 August 2023).
48. Chen, X.; Memon, H.A.; Wang, Y.; Marriam, I.; Tebyetekerwa, M. Circular economy and sustainability of the clothing and textile industry. *Mater. Circ. Econ.* **2021**, *3*, 12. [[CrossRef](#)]

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