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Review

# *Aloe vera* as Promising Material for Water Treatment: A Review

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**Abstract:** *Aloe vera* plant offers a sustainable solution for the removal of various pollutants from water. Due to its chemical composition, *Aloe vera* has been explored as coagulant/flocculant and biosorbent for water treatment. Most of the used materials displayed significant pollutants removals depending on the used preparation methods. AV-based materials have been investigated and successfully used as coagulant/flocculant for water treatment at laboratory scale. Selected AV-based materials could reduce the solids (total suspended solids (TSS), suspended solids (SS), total dissolved solids (TDS), and dissolved solids (DS)), turbidity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), heavy metals, and color, with removal percentages varied depending on the coagulant/flocculant materials and on the wastewater characteristics. In the same context, AV materials can be used as biological flocculant for wastewater sludge treatment, allowing good solid–liquid separation and promoting sludge settling. Moreover, using different methods, AV material-based biosorbents were prepared and successfully used for pollutants (heavy metal dyes and phenol) elimination from water. Related results showed significant pollutant removal efficiency associated with an interesting adsorption capacity comparable to other biosorbents derived from natural products. Interestingly, the enzymatic system of *Aloe vera* (carboxypeptidase, glutathione peroxidase, and superoxide dismutase) has been exploited to degrade textile dyes. The obtained results showed high promise for removal efficiencies of various kinds of pollutants. However, results varied depending on the methodology used to prepare the *Aloe vera* based materials. Because of its valuable properties (composition, abundance, ecofriendly and biodegradable), *Aloe vera* may be useful for water treatment.

**Keywords:** *Aloe vera*; water treatment; coagulation/flocculation; biosorbents; phytoremediation

## 1. Introduction

Industrial development generates large amounts of polluted effluents. Released in the environment, pollutants damage the soil, the ground, and the surface water—leading to ecosystem degradation and causing health risks [1–4]. In order to reduce the environmental problems associated with these effluents, industries utilize various methods of wastewater treatments. Depending on the characteristics of the wastewater, a combination of a number of physical, chemical, and biological processes can be applied to remove various pollutants (carbon, nitrogen, turbidity heavy metals, dyes, etc.) [5,6]. The physical methods include mainly the adsorption, ion exchange, and membrane technologies. The chemical treatment induces chemical reactions, coagulation, precipitation, oxidation, advanced oxidation, ion exchange, neutralization, and stabilization, etc. However, the biological treatment systems involve membrane bioreactors, biofilter, sequential batch reactor, activated sludge, etc. [7–10]. Although their ability to efficiently remove pollutants from various effluents, these processes may have some disadvantages such as the use of chemicals in the coagulation–flocculation technique. For example, aluminum salts and polyacrylamides remain in water after treatment and may cause health concerns (genotoxicity, neurotoxicity, etc.) for organisms [11,12]. Besides, the activated carbon used as adsorbent for wastewater treatment is expensive, non-selective, and needs regeneration after rapid saturation [13–15]. Therefore, depending on the characteristics of the industrial effluent, the applied process to remove pollutants may not be economically justified and sustainable, with a high environmental cost related to the adverse effects of its secondary effluent on the environment. In order to be sustainable, wastewater treatment should involve biological materials aiming to minimize energy consumption and negative impacts on the environment. As reported in the literature, the sustainable strategy involving the use of biological materials constitutes a promising solution for pollutants removal. For example, biological natural materials such as cactus, moringa, *Aloe vera*, bean, etc. have been explored for their eventual use for pollutants removal [16–18]. Interestingly, the removal of various pollutants (dyes, turbidity, metals, etc.) by *Aloe vera* (AV) via its utilization in many processes (adsorption, coagulation–flocculation, degradation, etc.) was reported. AV is biodegradable, safe, and abundant in various regions over the world. The literature reported the use of various methods to prepare AV-based materials. These AV materials have been adopted for water treatment, and various wastewater quality parameters (TSS, SS, TDS, DS, turbidity, COD, BOD, heavy metals concentration, color, etc.) were evaluated to determine their efficiencies in removing pollutants. In this context, a significant use of AV to remove various organic and inorganic pollutants was reported. This paper will review and discuss all the potential uses of AV for the removal of pollutants form wastewater.

## 2. *Aloe vera* as Coagulant/Flocculant for Wastewater Treatment

Coagulation/flocculation is a common process used for the removal of various pollutants (suspended solids, organic, and inorganic materials). In this operation, chemicals such as aluminum salts, acrylamides are added to water to destabilize colloidal materials and allow the agglomeration of small particles into larger settleable flocs [19,20]. However, these chemicals remain in treated water leading to various health problems (neurotoxicity, genotoxicity, etc.) [12]. Furthermore, during the treatment, these chemicals may react with other compounds producing new products with unknown health risks. Various diseases such as Alzheimer are reported to be related to the use of alum [21]. Therefore, it is necessary to consider alternative flocculants/coagulants. These alternative materials should be available, cost effective, biodegradable, and without health risks. Various parts (seeds, leaves, pieces, roots, fruits, etc.) of plants (cactus, moringa, etc.,) were used as potential sources of flocculants/coagulants [18,22]. Interestingly, the use of AV as a promising natural material to substitute chemicals in the coagulation/flocculation process [23–42] has been reported. Various investigations reported the use of AV as coagulant, flocculant, or coagulant/flocculant aid for water treatment. Figure 1 shows the scheme of *Aloe vera* preparations and applications for wastewater treatment using various processes.

To determine the process efficiency, various water quality parameters (solids, turbidity, color, COD, BOD, dyes, heavy metal, etc.) were measured. As reported in the literature, biopolymer investigations were designed and implemented in many stages, including mainly the material preparation and the optimization of the operating parameters (dosage, pH, temperature, mixing speed, contact time, etc.). Essentially, dosage is an important parameter to be studied and inadequate dosage could result in low performance of the coagulation/flocculation process [20]. In recent research conducted on AV, leaves gel was tested as coagulant aid for turbid water (35 NTU) treatment. For this purpose, the gel was blended and mixed with water (1%) in the presence of *Moringa oleifera*. The obtained results showed higher level of turbidity removal (91.42%) [23]. Similarly, 96.5% turbidity removal from Indrayani stream water was reached with 5 mg/L of liquid AV used as coagulation aid in the presence of alum (56 mg/L). However, for the same water and using the same quantity of alum (56 mg/L), the use of AV liquid as flocculant aid (10 mg/L) allowed the removal of 96.2% of the turbidity. Therefore, the use of liquid AV as coagulant aid offers more advantages (higher efficiency and lower quantity) than its use as flocculant aid. As indicated in the literature, many AV materials were prepared using different methods and applied for pollutants removal from waters. Sun dried AV offered a good potential as flocculant in reducing the turbidity (92.74%) and color (95.73%) from crude drinking water [24]. Likewise, textile wastewater was treated using flocculant recuperated after filtration of mixture of AV gel with distilled water [25]. The use of flocculant dose of 33 mL/L at pH 7.3, under mixing speed of 61 rpm for 20 min, allowed the removal of 92.3% of turbidity, 76.8% of COD, 83.5% of $BOD_5$, and 57.9% of TSS [25]. Similar work was conducted with high-loaded textile wastewater (1215 mg/L COD and 593.33 mg/L BOD) using powdered bioflocculant extracted from dehydrated pieces of AV leaves. The treatment of this effluent using bioflocculant dosage of 60 mg/L (at pH 5 and contact time of 180 min) removed 90.53% of COD, 98.19% of TSS, and 98.80% of TDS. Interestingly, the powdered bioflocculant exhibited significant flocculanting activity (82%) [26]. In the same perspective, methylene blue was partially removed (50–55%) using a coagulant obtained by physical blending of AV with aluminum sulphate (10:90%) performed at room temperature for 24 h. The removal rates were obtained at coagulant optimal dosage of 3000 mg/L and pH 6. The replacement of aluminum sulphate by magnesium sulphate for the preparation of AV coagulant allowed an enhancement of the removal efficiency of 60–70%, obtained at pH 12.5 and with the same dosage (3000 mg/L) [27]. Simultaneously to the removal of organic pollutants by the coagulation/flocculation process with AV, the removal of heavy metal was reported in few studies. For example, the AV powder (AV dried at 330 K) was tested for the removal of arsenic from aqueous solution (with initial concentration ranging from 0.2 to 1 mg/L). The use of 2 mg/L of the AV preparation as coagulant in the presence of polyaluminum chloride (3 mg/L) at pH 5 removed 92.63% of As (V) [28]. Similar preparation (AV powder used as coagulant) removed only 30.59% of Cu from river water (initial concentration 2000 mg/L). This removal rate was obtained with coagulant dose of 1.20 g/L, settling time of 40 min, pH 8, and at 313 K [29]. Interestingly, filtrate of AV gel was effective in the coagulation/flocculation of Pb (II) ions from textile wastewater. A removal rate of 77% was obtained with flocculant dosage of 33 mL/L at pH 7.3 [25]. Interestingly, results were comparable to those achieved when using cactus and *Moringa oleifera*. Moreover, the optimum AV coagulant/flocculant dose was found to be comparable to that reported for other used materials [18,30]. Table 1 summarized the experiments conducted for the removal of various pollutants by the coagulation–flocculation using AV.

**Table 1.** Pollutants removal by coagulation–flocculation using *Aloe vera*.

| Effluents | Preparation | Operating Conditions | Removal Efficiencies | Reference |
|---|---|---|---|---|
| River water<br>7 NTU | AV gel blended and mixed with H2O (1% *v/v*) | AV as coagulant aid (10 mg/L) with *Moringa oleifera* (10 mg/L) | Turbidity: 42.85% | [23] |
| 21 NTU | AV gel blended and mixed with H2O (1% *v/v*) | AV as coagulant aid (10 mg/L) with *Moringa oleifera* (50 mg/L) | Turbidity: 85.71% | [23] |
| 35 NTU | AV gel blended and mixed with H2O (1% *v/v*) | AV gel as coagulant aid (10 mg/L) with *Moringa oleifera* (100 mg/L) | Turbidity: 91.42% | [23] |
| Drinking raw water<br>Turbidity: 44,5 NTU<br>Color: 375 UPt-Co, pH 7 | Sun dried AV | 25 mg/L as flocculant | Turbidity: 92.74%<br>Color: 95.73% | [24] |

**Table 1.** *Cont.*

| Effluents | Preparation | Operating Conditions | Removal Efficiencies | Reference |
|---|---|---|---|---|
| Textile wastewater<br>Turbidity: 190 NTU<br>COD: 410 mg/L<br>BOD5: 335 mg/L<br>TSS: 380 mg/L<br>Pb: mg/L<br>pH 5.1, 37 °C | AV gel mixed H2O, stirred 30 min, strained (25 mm sieve) and filtrate recuperation | Flocculant dose: 33 mL/L, mixing time 20 min, pH 7.3, 61 rpm | Turbidity: 92.3%<br>COD: 76.8%<br>BOD5: 83.5%<br>TSS: 57.9%<br>Pb: 77% | [25] |
| Methylene blue | AV blended with magnesium sulphate (10:90%) at room temperature, 24 h | Dosage: 3000 mg/L as coagulant, pH 12.5 | 60–70% | [27] |
| Methylene blue | AV blended with magnesium sulphate (10:90%) at room temperature, 24 h | Dosage: 3000 mg/L as coagulant, pH 12.5 | 50–55% | [27] |
| As(V) aqueous solution (Na2HAsO4.7H2O) 0.2–1 mg/L | AV leaves washed with deionized water, cut into small pieces, dried (333 K), ground and sieved (100 mesh) | Dose of AV as coagulant: 2.0 mg/L, dose of polyaluminum chloride: 3 mg/L, pH 5 | 92.63% | [28] |
| As(V) aqueous solution: 0.2–1 mg/L | AV leaves washed with H2O, cut into small pieces, dried (333 K), ground and sieved (100 mesh) | 0.1 mg/L AV ascoagulant versus 3 mg/L polyaluminum chloridepH 5 | 21–93.1%. | [28] |
| River water<br>Cu: 2000 mg/L | AV powder | Coagulant dose: 1200 mg/L; settling time: 40 min, pH 8, 313 K | 30.59% | [29] |
| Indrayani stream water:<br>Turbidity: 45.5 NTU<br>Alkalinity: 70 mg/L,<br>pH 7.78 | | 56 mg/L of alum with 5 mg/L of liquid AV as coagulation aid | Turbidity: 96.5% | [31] |
| Indrayani stream water:<br>Turbidity: 101 NTU<br>Alkalinity: 65 mg/L. pH 7.1 | | 24 mg/L of alum with 14 mg/L of AV as coagulation aid | Turbidity: 98.5% | [31] |
| Indrayani stream water:<br>Turbidity: 45.5 NTU<br>Alkalinity: 70 mg/L,<br>pH 7.78 | AV blend | 56 mg/L of alum with 10 mg/L of liquid AV as flocculation aid | Turbidity: 96.2% | [31] |
| Indrayani stream water:<br>stream:<br>Turbidity: 101 NTU<br>Alkalinity: 65 mg/L<br>pH 7.1 | AV blend | 56 mg/L of alum with 10 mg/L of liquid AV as flocculation aid | Turbidity: 96.2% | [31] |
| Surface water<br>Turbidity: 40–100 NTU | AV gel blended and mixed with H2O | 4 mL/L, 308 K, pH 4–8 | Turbidity: 50–65% | [32] |
| Surface water<br>Turbidity: 12 NTU<br>TDS: 1472 mg/L<br>Color: 137 TCU | AV gel | 1 mL/L, pH 4.1, 303 K | Turbidity: 58.33%<br>TDS: 77.51%<br>Color: 50.36% | [33] |
| Surface water<br>Turbidity: 186.8 NTU<br>SS: 163 mg/L<br>Color: 278 (Pt/Co)<br>pH 7.37 | AV gel mixed with H2O, stirred and strained (25 mm mesh) and filtrate recuperation | Dose: 10 mL/L as flocculant | Turbidity: 72%<br>SS: 91%<br>Color: 15% | [34] |
| Textile wastewater<br>COD: 1215 mg/L<br>BOD: 593.33 mg/L<br>TSS: 3768 mg/L<br>TDS: 3754 mg/L | Powdered bioflocculant extracted from dehydrated pieces of AV leaves (313 K) | Dosage: 60 mg/L, pH 5, contact time: 180 min | FA: 82%<br>COD: 90.53%<br>TSS: 98.19%<br>TDS: 98.80% | [35] |
| Municipal wastewater<br>Turbidity: 54.1–66.1 NTU<br>TDS: 734.12–784.09 mg/L<br>TSS: 218.22 to 239.10 mg/LpH 7.2–8.4 | AV gel blended and mixed with H2O | 150 mL of AV gel, 10 mL of alum as coagulant, pH 8 | Turbidity: 67.72% | [35] |

**Table 1.** *Cont.*

| Effluents | Preparation | Operating Conditions | Removal Efficiencies | Reference |
|---|---|---|---|---|
| Electroplating industrial wastewater: BOD5: 32.5 mg/L COD: 220 mg/L DS: 9.4 mg/L SS: 3540 mg/L Cr(VI): 785 mg/L, pH 2.6 | Frozen AV gel (277 K), extracted and lyophilized | AV polymer: 0.50–2.5 g/L, Aluminum sulphate: 500–1000 mg/L, pH: 2.5–5.5 | Cr(VI): 6.37–37.74% DS: 89.80–94.13% SS: 71.06–90.00% | [36] |
| Dye industry effluent TDS: 6389 mg/L COD: 415.7 mg/L BOD: 150 mg/L | AV gel | 100 g of AV gel (20%, 40%, 60%, 80%, and 100%) added to water at boiling temperature | TDS: 1.8–3.5% COD: 3.23–33.05% BOD: 15.78–53.33% | [37] |
| River water Cu: 2000 mg/L | AV powder | Coagulant dose: 1200 mg/L; settling time: 40 min, pH 8, 313 K | 30.59% | [29] |
| River water Cu: 2 g/L | AV powder | Coagulant dose:1200 mg/L; settling time: 40 min, pH 8, 313 K | 30.59% | [29] |
| Municipal wastewater Turbidity: 176 NTU. TSS: 3.4635 mg/L | AV pulp blended, 1000 mg was mixed with 100 mL of H2O | Dosage of 3 mL (30% AV pulp), pH 6–7 | Turbidity: 77.05% TSS: 74%. | [38] |
| Synthetic water: Turbidity: 55.0 NTU COD: 376.23 mg/L pH 7.4 | AV leaves gel | 1%, 2% and 5% of AV gel | Turbidity: 51.72% COD: 59.20% | [39] |
| Tannery Wastewater Turbidity: 74.43 NTU COD: 502.6 mg/L pH 7.8 | AV leaves gel | 5% of AV gel | Turbidity: 46.76% COD: 52.60% | [39] |
| Artificial turbid water Turbidity: 70–90 NTU | AV gel blended and mixed with H2O (1% *v*/*v*) | AV as coagulant aid (7%) with alum (10 mg/L) | Turbidity: 76–81% | [40] |
| Artificial turbid water Turbidity: 20–30 NTU | AV gel blended and mixed with H2O (1% *v*/*v*) | AV as coagulant aid (7%) with alum (10 mg/L) | Turbidity: 60–65%. | [40] |

AV: *Aloe vera*, TSS: total suspended solids, TDS: total dissolved solids, SS: suspended solids, DS: dissolved solids, FA: Flocculating activity. BOD: biochemical oxygen demand, COD: chemical oxygen demand.

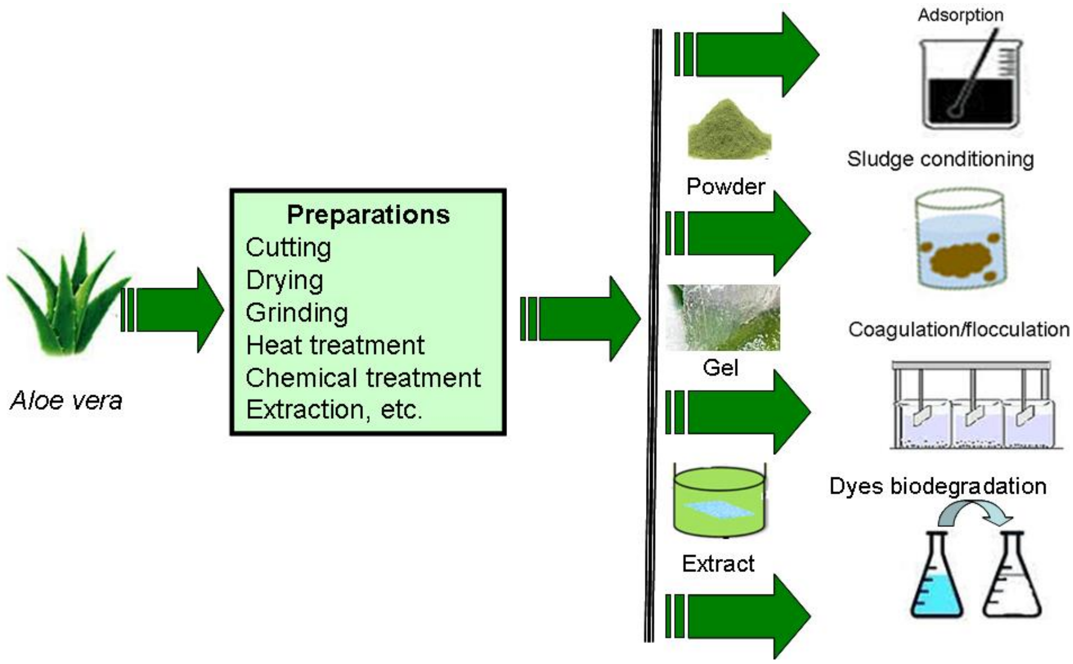


**Figure 1.** The scheme of *Aloe vera* preparations and applications for wastewater treatment.

Generally, experiments related to the use of AV materials in the coagulation/flocculation process for wastewater treatment showed the variability of the efficiencies in removing pollutants. This variability could be related mainly to the method used to prepare AV polymer and to the characteristics of the wastewaters. The wastewater characteristics considerably controlled the process efficiency, as reported for other materials [15,17,18,30,41].

## 3. *Aloe Vera* as Biosorbent for Pollutant Removal

The beneficial characteristics of the adsorption process (efficiency, safety, technical feasibility, simple design, easy processing, etc.) allowed its application for the treatment of wastewater containing various pollutant types (dyes, metals, phenols, etc.). A material suitable as absorbent should be ecofriendly, cheap, resistant to toxic substances, able to remove various inorganic and organic pollutants, and offer high surface area and porosity [17,42]. In order to determine the suitability and the applicability of an adsorbent in removing pollutant, equilibrium modelling, kinetics and thermodynamic parameters should be determined based on experimental data [42,43]. Generally, Langmuir, Freundlich, Temkin, Dubinin-Radushkevicz, and the Halsey isotherm models were applied to analyze the equilibrium adsorption data. However, Elovich equation, intra particle diffusion pseudo first order, and pseudo second order models were used to describe the obtained kinetics results data [44–46]. In order to substitute the activated carbon, various renewable materials (plants, agricultural by-products, industrial wastes, etc.) were tested as adsorbents [17,47–49]. Among the studied materials, AV-based materials were considered as an adsorbent for water treatment. The removal of pollutants, mainly from aqueous solutions using AV as biosorbent, was examined by many researchers (Table 2).

**Table 2.** *Aloe vera* as biosorbents for pollutants removal.

| Effluents | *Aloe vera* Preparation | Removal Efficiency (R in %)/Biosorption Capacity (q in mg/g)/Used Conditions/Isotherm | References |
|---|---|---|---|
| Cd(II) aqueous solution (20–50 mg/L) | AV leaves crushed, powdered and sieved (200 mesh) and modified with carboxylated carbon nanotubes | R: 98%, q: 46.95 mg/g, dosage: 0.02 g, contact time: 30.45 min, pH 6.37 and initial cadmium concentration: 10.69 mg/L, Langmuir | [50] |
| Ni(II) aqueous solution (20–200 mg/L) | AV leaf residue: steam-heated (40–50 Ka, 20–30 min), washed with H2O, dried (353 K, 24 h), grinded, sieved (100 mesh). The obtained powder mixed with Na2CO3 solution (250 rpm, 12 h), filtered, washed with H2O | q: 28.98 mg/g, 303 K, dosage: 600 mg/L, contact time: 90 min, pH 7. Pseudo-first-order, Langmuir | [51] |
| Th and Ba aqueous solutions (5–200 mg/L) | AV gel dried (333 K), grounded, sieved (<125 µm), treated with H3PO4 (1.5 M), filtered, rinsed with H2O and dried (333 K). | Th: q: 96.2 mg/g, Langmuir<br>Ba: q: 47.62 mg/g, Freundlich | [52] |
| Aqueous solutions (Th and Ba: 5–200 mg/L) | AV gel dried (333 K), grounded, sieved (<125 µm), treated with H3PO4 (1.5 M), filtered, rinsed with H2O and dried (333 K). | Th: q: 170 mg/g, Langmuir<br>Ba: q: 107.5 mg/g, Freundlich | [52] |
| As aqueous solution (43,000 mg/L) | AV leaves | R: 100%, dosage: 30,000 mg/L, contact time: 4 h | [53] |
| Cr(VI) aqueous solution (50 mg/L) | AV treated with H2SO4 | R: 98.66%, q: 58.83 mg/g, dosage 2000 mg/L, pH 1.23, 150 min, 150 rpm, 298 K, Langmuir | [54] |
| Cr(VI) aqueous solution (50 mg/L) | AV HNO3 activated carbon | R: 98.89%, q: 59.88 mg/g, dosage 2000 mg/L, pH 1.21, 90 min, 150 rpm and 298 K, Langmuir | [54] |

**Table 2.** *Cont.*

| Effluents | *Aloe vera* Preparation | Removal Efficiency (R in %)/Biosorption Capacity (q in mg/g)/Used Conditions/Isotherm | References |
| --- | --- | --- | --- |
| Pb(II) aqueous solution (400–2000 mg/L) | AV leaves dust and cut into small pieces, dried at room temperature (2 weeks), re-dried (323–333 K, 3 h), powdered, sieved (53–74 μm) and treated with H3PO4 (1 M), filtered and washed with distilled water | R: 96.2% when the adsorbent amount was increased from 2000 to 6000 mg/L for an agitation time of 30 min. Langmuir and Freundlich isotherms | [55] |
| Cu(II) aqueous solutions (20,000–70,000 mg/L) | Leaves dried, grinded and sieved (0.2–0.3 μm) | q: 2.27 mg/g, dosage 2 g/L, contact time: 2 h, initial concentration 20,000 mg/L, pH 5, 318 K. Langmuir | [56] |
| Hg(II) aqueous solution (5–15 mg/L) | Ethanolic AV extract reduced using AgNO3 (12 mM) at pH 7, in presence of air (stirred, 330 K, 3 h), then heated (353 K, 2 h) and filtered (0.45 μm). | R: 95% | [57] |
| Pd(II) aqueous solution (5–600 mg/L) | AV shell ash magnetic nanoparticles | q: 47.2 mg/g, dosage: 2000 mg/L, contact time: 15 min, pH 5, 298 K, Freundlich | [58] |
| Textile wastewater (Pb: 0.11 mg/L) | AV gel dried (353 K for 24 h), redried using muffle furnace (673 K for 30 min) | R: 78%, dosage: 20 mg/L, contact time: 60–90 min | [59] |
| Cu (II) aqueous solutions (40–120 mg/L) | Zinc oxide AV nanoparticles: AV gel broth extracts (90%) mixed with zinc nitrate (94,000 mg/L), stirred (120 min) and left at rest (12 h), then dried (1023 K, 1 h) | R > 95%, q: 20.425 mg/L, 298 K, pH 4, 150 min, Langmuir | [60] |
| U(VI) and Cd(II) aqueous solution (1000 mg/L) | Outer layer AV leaves was dried (333 K), grounded, sieved (<125 μm), treated with H3PO4 (1.5) and NaOH (1.5) (24 h at room temperature), filtered, rinsed (H2O) and dried (353 K) | U (VI): q: 370.4 mg/g, dosage: 1.5 g/L, 6 h, pH 4 Cd(II): q: 104.2 mg/g, mg/g, dosage: 1.5 g/L, 6 h, pH 5–6, Langmuir and Freundlich | [61] |
| Aqueous solutions: Ag (I) | AV shell ash supported Ni0.5Zn0.5Fe2O4 magnetic nanoparticles: AV shells were washed, dried (air oven, 353 K, 24 h), ground, sieved, then carbonized (973 K, 2 h), mixed with metal nitrates and dissolved in H2O. The extract mixed with the previous solution and stirring (30 min), evaporated (353 K), ground and calcined (823 K, 2 h). | R: 98.3%, q: 243.90 mg/g, dosage: 4000 mg/L, 30 min, pH 5, initial concentration: 100 mg/L Langmuir and Freundlich | [62] |
| Aqueous solution of malachite green (50–250 mg/L) | Activated AV stems carbon: carbonized with concentrated sulphuric acid, washed with water and activated around (1273 K, 6 h) | q: 334.61 mg/g, 303 K, 50 min, pH 6.5, Langmuir | [63] |
| Aqueous solution of methylene blue (4000 mg/L) | Reduced graphene oxide using AV | R: 98%, dosage 20 mg, 298 K,150 rpm, pseudo second order | [64] |
| Aqueous solution of methylene blue (1000 mg/L) | Outer layer of AV leaves dried (353 K, overnight), crushed, and sieved (<180 μm) | q: 356 mg/g, 300 K Langmuir | [65] |
| Aqueous solution of reactive red RR198 and reactive blue RB19 (10–160 mg/L) | AV leaves dried (378 K, 10 h), ash preparation (573 K, 2 h), sieved (149–74 μm) | RR-198: R: 80%, q: 80.152 mg/g RB-19: R: 90%, q: 88.452 mg/g pH 3, 20 min, 308 K Freundlich | [66] |
| Aqueous solution of Aqueous solution of reactive violet (RV8) and congo red (CR) (5.0–40 mg/L) | AV leaves washed (H2O and ethanol), dried (1 h), powdered, sieved (200 mesh), mixed with CuCl2 and Mg powder (stirred 60 min), filtered, washed (H2O and ethanol), dried (323 K, 1 h), grounded and sieved (200 mesh) | CR: q: 36.90 mg/g RV8: q: 25.19 mg/g dosage: 100 mg/L, pH 5.5, 30 min, initial concentration: 10 mg/L. Langmuir and Freundlich | [67] |

**Table 2.** *Cont.*

| Effluents | *Aloe vera* Preparation | Removal Efficiency (R in %)/Biosorption Capacity (q in mg/g)/Used Conditions/Isotherm | References |
|---|---|---|---|
| Aqueous solution of congo red (1000 mg/L) | AV leaves dried, boiled (in H2O), extract mixed with copper sulphate and separation of CuO nanoparticles | Q: 1.1 mg/g, dosage: 5 mg/g, contact time: 10 min, pH 2, Langmuir | [68] |
| Synthesized wastewater (Titan Yellow: 10,000–100,000 mg/L) | Air-dried AV: AV leaves washed, cut into small pieces, air dried, dried in (323–325 K for 2 h), ground, and sieved (1 mm mesh) | R: 79.44%, q: 55.25 mg/g, dosage: 200 mg/50 mL, pH 9, contact time: 30 min, and initial concentration: 100,000 mg/L, Langmuir | [69] |
| Synthesized wastewater (Titan Yellow: 10,000–100,000 mg/L) | Thermally treated AV: air-dried AV treated at 573–773 K (1 h) | R: 31.08–70.85%, q: 4.662–10.63 mg/g, dosage: 4000 mg/L, pH 9, contact time: 30 min, and initial concentration: 100,000 mg/L | [69] |
| Synthesized wastewater: aniline and methyl orange (MO) (20–100 mg/L) | AV leaves wastes-based sulfuric acid modified activated carbon: AV gel washed (H2O), dried (423 K, 24 h), crushed (30–60 µm), carbonization (823 K, 20 min), H2SO4 (0.1) treatment (12 h), filtered, washed (H2O), dried (423 K, 12 h), crushed and sieved (40-mesh) | aniline: q: 185.18 mg/g MO: q: 196.07 mg/g, dosage: 1000 mg/L, contact time: 60 min, pH 3, 300 K Freundlich | [70] |
| Solution of phenol (0.1–64 mg/L) | AV leaves dried (378 K, 3h), burned (973 K, 1 h), milled, converted to nanoscale (stearic acid 3%) | R > 96%, q: 71.73 mg/g, dosage: 80 mg/L, initial concentration: 32 mg/L, contact time: 60 min, 328 K), pH 7, Freundlich and Langmuir | [71] |

As reported in Table 2, various metals were removed using AV gel and leaves (treated and untreated materials). The adsorption process is controlled by many factors including mainly the AV preparations and operating parameters (metal initial concentration, dosage, pH, temperature, contact time, etc.). For example, AV leaves were crushed, powdered, sieved (200 mesh) and modified with carboxylated carbon nanotubes to be used to remove Cd(II) from aqueous solution (20–50 mg/L). High level of adsorption (98%) was obtained at 20 mg, pH 6.37, and initial concentration of 10.69 mg/L. The adsorption process was found to fit with Langmuir model [51]. Furthermore, AV leaves treated with $H_2SO_4$ allowed high removal of Cr(VI) (98.66%), with maximum adsorption ability of 58.83 mg/g obtained with a dosage of 2000 mg/L and pH 1.23 [54]. Under the same condition, the treatment of AV with $HNO_3$ activated carbon allowed the same removal rate (98.89%) for Cr(VI) [54]. Interestingly, total as removal was achieved using AV leaves with a dosage of 30,000 mg/L and a contact time of 4 h [54]. Another biosorbent was prepared by Malik et al. (2015), using AV leaves to remove Pb(II) from water. Leaves were cut, dried at room temperature (for 2 weeks), dehydrated (3 h at 323–333 K), powdered, sieved (53–74 µm), and activated with $H_3PO_4$ (1M), then filtered and washed with $H_2O$. The obtained material reached an adsorption efficiency of 96.2% [55]. However, another AV preparation allowed the removal of only 78% of Pb(II) from textile wastewater. In this preparation, AV gel was washed, dried (1073 K for 24 h), and activated 30 min using muffle furnace (4273 K) [59]. Ni(II) removal was also investigated using steam-heated AV leaves (at 40–50 Ka for 20–30 min). After drying (353 K, 24 h), grinding, and sieving (100 mesh), the obtained powder was mixed with $Na_2CO_3$ solution, filtered, washed with distilled water (until pH constant) and dried (353 K for 24 h). Of this preparation, 600 mg reached a maximum adsorption capacity of 28.98 mg/g obtained at pH 7, 303 K, and contact time of 90 min. The adsorption process was found to fit with Langmuir model [51]. Likewise, the Th and Ba removal ability by AV gel modified with $H_3PO_4$ or NaOH was reported by Kapashi et al. (2019). Compared to $H_3PO_4$, the use NaOH enhances Th and Ba sorption capacity of AV gel. For Th, the adsorption capacity passed from 96.2 mg/g (with $H_3PO_4$ treatment) to 170 mg/g (with NaOH treatment). However, for Ba these values were 47.62 mg/g and 107.5 mg/g, respectively. The highest adsorption offered by AV gel treated with NaOH, may be contributed to NaOH effect which may enhance the surface available for metal sorption more importantly than $H_3PO_4$ [52]. In another study, removal of Hg(II) from aqueous solution (5–15 mg/L) was assessed using AV ethanolic extract reduced with $AgNO_3$ (12 mM). This extract allowed 95% Hg(II) removal [57]. Generally, AV materials exhibit acceptable heavy metal removal while compared to other natural products (Table 3) and the result variability is related to biosorbent preparation methods and operating parameters (pH, temperature, contact time, biosorbent dose, heavy metal initial concentration, etc.).

**Table 3.** Maximum adsorption capacity of *Aloe vera* based biosorbents compared to other natural products for Ni(II), Cu(II), Cd(II) and Cr(VI).

| Adsorbents | Adsorption Capacity (mg/g) | References |
|---|---|---|
| **Ni(II)** | | |
| Steam-heated AV leaves ($Na_2CO_3$ treatment) | 28.98 | [51] |
| *Imerata cylindrical* ($H_2SO_4$ treatment) | 19.13 | [72] |
| *Oak sawdust* (HCl treatment) | 3.37 | [73] |
| *Dalbergia sissoo* (NaOH treatment) | 10.47 | [74] |
| **Cu(II)** | | |
| Dried AV leaves | 2.27 | [56] |
| Tobacco leaves | 17.182 | [75] |
| *Tectona grandis* L.f. leaves | 15.43 | [76] |
| *Ricinus communis* leaves | 127.27 | [77] |
| **Cd(II)** | | |
| Outer layer of AV leaves (treatment with $H_3PO_4$ and NaOH) | 104.2 | [61] |
| Sesame waste | 84.74 | [78] |
| *Ficus religiosa* leaves | 27.14 | [79] |
| **Cr(VI)** | | |
| AV leaves (treatment with $HNO_3$ activated carbon) | 59.88 | [54] |
| *Melaleuca diosmifolia* leaves | 62.5 | [80] |
| *Ficus auriculata* leaves | 6.8 | [81] |

Adsorbent derived from AV are also evaluated for the removal of dyes. In this perspective, various preparations of AV were tested as biosorbents for dye decolorization. AV leaves were subject to treatments including simple air-drying, heat treatment, treatments with chemicals (ethanol, $H_2SO_4$, NaOH, stearic acid, etc.) and mixed with other components ($CuCl_2$, copper sulphate, etc.) as indicated in Table 2. For example, outer layer of AV leaves were subject to dehydration at 353 K (overnight) before being used for the removal of methylene blue from aqueous solution. The final adsorbent materials were crushed and sieved (<180 µm). The obtained adsorbent showed biosorption capacity of 356 mg/g [66]. For the same dye, significant removal efficiency (98%) was obtained with reduced graphene oxide using AV [64]. For the same purpose, AV leaves were used for the removal of reactive violet and congo red. Powdered leaves were mixed with $CuCl_2$ and Mg powder (stirred for 60 min), filtered, washed ($H_2O$ and ethanol), dried (323 K, 1 h), ground, and then sieved (200 mesh). Hence, the prepared materials allowed better adsorption capacity for congo red (36.90 mg/g), than reactive violet 8 (25.19 mg/g) obtained at dose of 100 mg, pH 5.5, contact time of 30 min, and initial concentration of 10 mg/L [67]. However, lower adsorption capacity for congo red (1.1 mg/g) was obtained with the preparation suggested by Batool et al. (2019), in which AV leaves water extract was mixed with copper sulfate solution [68]. For the removal of titan yellow, two preparation methods (air-dried and thermally treated AV) were applied. Air-dried AV leaves (in an oven at 323–325 K, 2 h) were ground and sieved (1 mm), and then used to treat synthesized wastewater (10,000–100,000 mg/L). The obtained powder removed 79.44% of titan yellow with maximum sorption capacity of 55.25 mg/g obtained with a dosage of 4000 mg/L, pH 9, contact time of 30 min, and initial concentration of 100,000 mg/L [69]. However, for the thermally treated AV leaves, the removal efficiency did not exceed 70.85% under the same condition as reported before [69].

Furthermore, the removal of phenol from water was performed using dried AV leaves converted to nanoscale using stearic acid (3%). Interestingly, more than 96% of phenol was removed with an adsorption capacity of 71.73 mg/g achieved with a dosage of 80 mg/L, initial phenol concentration of 32 mg/L, contact time of 60 min at pH 7, and 328 K [71].

Generally, AV offered dye adsorption ability comparable to other biosorbents derived from natural products (Table 4). As indicated for heavy metals, the decolorization process is controlled by various factors including the preparation methods for the adsorbent materials and the parameters applied during the biosorption (dosage, contact time, pH, temperature, initial concentration, etc.). The adsorption process is related to the functional groups present over the biosorbent surface. Interestingly, the treatment process may enhance the specific surface area and the adsorption index of the material [82–84].

**Table 4.** Maximum adsorption capacity of *Aloe vera* based biosorbent compared to other natural products for methylene blue and methyl orange.

| Adsorbent Based Materials | Adsorption Capacity (mg/g) | References |
|---|---|---|
| **Methylene blue** | | |
| Dried outer layer of AV leaves | 356 | [65] |
| Cactus (fruit peels treated with $H_3PO_4$) | 416 | [82] |
| Cactus (pear seed cake treated with $H_3PO_4$) | 260 | [85] |
| Cactus cladodes | 3.44 | [86] |
| Cactus fruit peel | 222 | [87] |
| Black stone cherries | 321.75 | [88] |
| Walnut shell | 315 | [89] |
| Hazelnut husks | 204 | [90] |
| Wood apple rind | 40 | [91] |
| **Methyl orange** | | |
| AV gel (dried and treated with $H_2SO_4$) | 196.07 | [70] |
| Untreated corn leaves | 675.6 | [92] |
| Corn leaves (treated with HCl) | 4.54 | [92] |
| Sugar scum | 15.24 | [85] |
| Cork powder | 16.66 | [93] |

## 4. *Aloe vera* Gel as Flocculant for Wastewater Sludge Treatment

Sludge gravity settling is improved using mineral salts and synthetic polymers. This process is called sludge conditioning. As reported for the coagulation/flocculation, the used chemicals are associated to various environmental problems [12,21]. Consequently, the use of natural products as bioflocculant for sludge conditioning constitutes a new strategy with sustainable impacts. To the best of our knowledge, the only study reporting the use of AV as biological flocculant for wastewater sludge treatment was conducted recently by Jaouadi et al. (2020) [94]. In this study, AV gel was blended and used freshly as bioflocculant. Interestingly, the gel allowed good sludge solid–liquid separation. Moreover, a combined treatment using AV gel and water glass (3%) enhanced the particles size and promoted sludge settling. At the same time, AV gel promoted the odor removal from the sludge, which was confirmed by volatile organic compounds analysis [94]. The use of AV materials as conditioner for wastewater sludge treatment represents a processing technology in line with the sustainable development goals. However, the applicability of this biomaterial should be confirmed by the evaluation of various parameters (dryness, residual turbidity and resistance of filtration) and compared to that obtained while using polyelectrolytes ($FeCl_3$, $Al_2(SO_4)_3$, etc.).

## 5. *Aloe vera* for Textile Dyes Biodegradation

Because AV contains enzymes, the degradation of dyes (congo red and malachite green) was examined using water extract of different plant parts (pulp, skin, and whole plant) by Rai et al. (2014), as the only group of researchers reporting this phytoremediation [95]. Dye decolorization rate varied depending on the extract origins. Malachite green decolorization reached the maximum in the presence of pulp extract (30%). However, skin extract allowed maximum decolorization for congo red (27%). Dye transformation is related to the presence of enzymes in AV, such as carboxypeptidase, glutathione peroxidase, as well as several isozymes of superoxide dismutase [96]. These enzymes are studied in different plants and microorganisms and are shown responsible for the degradation of dye molecules [97,98]. Consequently, AV enzymes can be considered as a biological option useful for treating textile wastewater. Similarly to various plants, AV exhibit phytoremediation potential for dyes remediation, as indicated in Table 5 for malachite green. The decolorization rate varied depending on the operating conditions applied for each experiment (pH, temperature, time, dye concentration, dose, etc.). Generally, more investigations are needed to explore the operating conditions for enzymatic system and to determine the compounds resulted from the biodegradation process.

**Table 5.** Comparison of phytoremediation potential of various plants for malachite green degradation.

| Textile Dyes | Decolorization Rate (%) | References |
|---|---|---|
| AV pulp | 30 | [95] |
| AV skin | 10 | [95] |
| AV whole plant | 9 | [95] |
| Cactus cladode | 99 | [99] |
| Cactus callus | 91 | [99] |
| *Azolla pinnata* | 84.4 | [100] |
| *Lemna minor* | 88 | [101] |
| *Spirodela polyrhiza* | 95 | [102] |

## 6. Factors Making *Aloe vera* a Promising Material for Water Treatment

*Aloe vera* is characterized by its original composition including enzymes, vitamins, carbohydrates lignin, proteins, and inorganic substances with beneficial utilization in various fields (food industry, pharmaceutical industry, cosmetics, etc.) [103,104]. The adsorption is related to the presence of high fiber content in AV gel, and hydroxyl and carboxyl groups allowed metal binding on AV materials [25]. Moreover, AV extract demonstrated its ability to play the role of metal reducing agent [105–107]. Glyco-aloe-modinanthrone and tannins are reported to be responsible of the coagulation property similar to other natural flocculants such as cactus juice [18]. In fact, AV gel is composed mainly of polysaccharide with low protein and lipid contents, and polysaccharide mucilage is involved in the flocculation/coagulation process. In this context, cactus carbohydrates (L-arabinose, D-galactose, L-rhamnose, D-xylose, and galacturonic acid) have been reported to be implicated as coagulant agent [108]. For example, galacturonic acid with its polymeric structure allowed the adsorption of particles via bridges. In addition to that, polysaccharide functional groups (carboxyl, hydroxyl, and amine) and hydrogen bonds are useful for the flocculation [109]. Furthermore, the mucilage property is controlled by the presence of $Ca^{2+}$ and $K^{+}$, which enhance its water holding capacity [110]. This behavior is behind the use of this material for sludge dewatering. Interestingly, AV enzymatic system (carboxypeptidase, glutathione peroxidase, as well as several isozymes of superoxide dismutase) can be considered as a biological option useful for dyes biodegradation. However, the AV composition varied depending on various factors (species, origin, etc.), which may affect the coagulation property [111,112].

## 7. Conclusions

*Aloe vera* is an interesting plant that should be considered in water treatment. The possibility of using various AV reparations for pollutants removal from water was proved. It can be used as a flocculant/coagulant, as a biosorbent, and can substitute polymer in sludge dewatering. The use of AV materials in the coagulation/flocculation process for wastewater treatment has been verified at laboratory scale showing significant results in removing pollutants (suspended solids, turbidity, COD, BOD, dye, and heavy metals) from water. In some cases, the efficiency of pollutant removal exceeded 90% depending on the AV preparations used as coagulant/flocculant and on the wastewater characteristics. AV polymers are also useful for wastewater sludge conditioning. Furthermore, AV-based biosorbents were prepared using various methods, including sun-drying, heat treatment and chemical treatments. The resulted materials were tested for dye and metal removal. The adsorption capacity is controlled by various factors including the preparation techniques, the pollutant types, and the operating parameters (adsorbent dose, pH, temperature, contact time, etc). Experimental data showed promising removal values comparable to other materials reported in the literature. Interestingly, AV offered an enzymatic system able to degrade textile dyes. Generally, experiments were conducted at laboratory scale using aqueous solutions of pollutants. Consequently, more researches are needed to evaluate the applicability of AV materials for real wastewater at large scale. In this context, it is very important to optimize the operating conditions for each type of wastewater. Moreover, environmental study should be addressed taking into consideration the AV material properties useful as coagulant/flocculant or as biosorbent. Material properties include life cycle, storage condition, biodegradation, alteration, regeneration, etc. Finally, *Aloe vera* is abundant, ecofriendly, biodegradable, and environmentally sustainable. However, techno-economic assessment is required after confirmation of its applicability at real conditions.

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