Inexpensive Organic Materials and Their Applications towards Heavy Metal Attenuation in Waters from Southern Peru

Pablo Garcia-Chevesich 1,2,*, Vilma García 3, Gisella Martínez 3, Julia Zea 3, Juana Ticona 3, Francisco Alejo 3, Johan Vanneste 1, Sarah Acker 1, Gary Vanzin 1, Aaron Malone 1, Nicole M. Smith 1, Christopher Bellona 1 and Jonathan O. Sharp 1

1 Center for Mining Sustainability, Colorado School of Mines, Golden, CO 80401, USA; vanneste@mines.edu (J.V.); sarahacker@mymail.mines.edu (S.A.); gvanzin@mines.edu (G.V.); amalone@mines.edu (A.M.); nmsmith@mines.edu (N.M.S.); cbellona@mines.edu (C.B.); jsharp@mines.edu (J.O.S.)
2 International Hydrological Programme, UNESCO, Montevideo 11600, Uruguay
3 Centro de Minería Sostenible, Universidad Nacional de San Agustín de Arequipa, Arequipa 040000, Peru; dgarciaf@unsa.edu.pe (V.G.); omartinez@unsa.edu.pe (G.M.); jzeaa@unsa.edu.pe (J.Z.); jticonaq@unsa.edu.pe (J.T.); falejo@unsa.edu.pe (F.A.)
* Correspondence: pchevesich@mines.edu; Tel.: +1-520-270-9555

Received: 10 September 2020; Accepted: 13 October 2020; Published: 21 October 2020

Abstract: There is interest in using locally available, low cost organic materials to attenuate heavy metals such as Cd, Cr, Cu, Hg, Ni, Pb, and Zn found in surface waters in Peru and other developing regions. Here we mesh Spanish language publications, archived theses, and prior globally available literature to provide a tabulated synthesis of organic materials that hold promise for this application in the developing world. In total, nearly 200 materials were grouped into source categories such as algae and seashells, bacteria and fungi, terrestrial plant-derived materials, and other agricultural and processing materials. This curation was complemented by an assessment of removal potential that can serve as a resource for future studies. We also identified a subset of Peruvian materials that hold particular promise for further investigation, including seashell-based mixed media, fungal blends, lignocellulose-based substrates including sawdust, corn and rice husks, and food residuals including peels from potatoes and avocados. Many studies reported percent removal and/or lacked consistent protocols for solid to liquid ratios and defined aqueous concentrations, which limits direct application. However, they hold value as an initial screening methodology informed by local knowledge and insights that could enable adoption for agriculture and other non-potable water reuse applications. While underlying removal mechanisms were presumed to rely on sorptive processes, this should be confirmed in promising materials with subsequent experimentation to quantify active sites and capacities by generating sorption isotherms with a focus on environmental conditions and specific contaminated water properties (pH, temperature, ionic strength, etc.). These organics also hold promise for the pairing of sorption to indirect microbial respiratory processes such as biogenic sulfide complexation. Conversely, there is a need to quantify unwanted contaminant release that could include soluble organic matter and nutrients. In addition to local availability and treatment efficacy, social, technical, economic, and environmental applicability of those materials for large-scale application must be considered to further refine material selection.

Keywords: heavy metals; Peru; remediation; sorption; water treatment
1. Introduction

Heavy metals impair water supplies globally (e.g., [1]). Heavy metals are a group of elements with high density (generally greater than 6 g/cm$^3$) [2] including Cd, Cr, Cu, Hg, Ni, Pb, and Zn. Common characteristics of heavy metals in the environment are persistence, bioaccumulation, biotransformation [3], and toxic implications for human and environmental health [4]. Once ingested, these metals are not easily eliminated, which can lead to bioaccumulation and damage of internal organs, resulting in chronic and terminal diseases (e.g., [5]).

A wide variety of technologies have been developed and applied globally for the removal of heavy metals from polluted waters, including chemical precipitation, ion exchange, membrane filtration (electrodialysis, reverse osmosis, nanofiltration, ultrafiltration), electrocoagulation, recovery by evaporation, coagulation-flocculation, flotation, solvent extraction, and electrolysis reduction [6]. While effective for contaminant attenuation, these treatment approaches collectively necessitate high operating costs, generate sludge, demand additional chemicals to function properly, and require centralized and skilled operational management by centralized water treatment plants [7]. These limitations necessitate exploring alternatives to remove heavy metals from polluted waters for use in remote locations and developing countries where resources are limited, as well as towards agricultural and other non-potable water applications.

Additional promise for metal attenuation resides in the application of locally abundant, affordable, and renewable organic materials. This has been explored globally in places as diverse as Taiwan [8], Turkey [9], India [12–15], Nigeria [16], Serbia [17], Saudi Arabia [18,19], Egypt [20], Jordan [21], Poland [22], and Malaysia [23], among many others. Since earlier publications (e.g., [24]), several reviews have synthesized these findings and applications with a particular focus on the developing world, including those conducted by [14, 25–27].

With this in mind, it is important to continue expanding the geographic scope of this focus on regionally available and inexpensive materials for heavy metal removal to include additional world regions such as Latin America, where less research has been done. For example, crop irrigation with regional waters generates local food crops in southern Peru that often exceed public and environmental health standards for heavy metals [28]. River water impairment in the area is caused by both natural and anthropogenic causes [29–31]. The volcanoes and high-altitude formations of the Andes mountain range have emitted magmatic products such as ashes, pyroclastic flows, and lahars (in addition to geysers) that contribute metal(loid) elements into the local fluvial system. Metallogenetic deposits in the region (gold, copper, and silver, among others) are created by the contribution of magmatic solutions in existing rocks that in turn affect fluvial and terrestrial ecosystems with heavy metals, which can be enriched when water passes through host rocks [32]. Similarly, anthropogenic activities including agriculture and mining further contribute to heavy metal release into rivers and aquifers [29,33]. Mining has been practiced across the region since pre-colonial times, creating a dispersed landscape of legacy and active sites, ranging from artisanal to large-scale [34]. Precise attribution of contaminant origins is difficult in this context, which means remediation must typically be undertaken at public expense. Given these realities, social, technological, and economic barriers hinder adequate water treatment needed to protect human and ecological health [35].

To this end, this literature-based synthesis and tabulation of materials focuses on combining results of studies conducted with organic materials in southern Peru (Arequipa region) with others from developing countries. In addition to those available in peer-reviewed English-language literature, we curated and contextualized local findings, many of them in Spanish, including theses housed at the Universidad Nacional de San Agustín de Arequipa (UNSA), other local universities, and federal reports from the Autoridad Nacional del Agua (ANA). Performing this type of meta-analysis capitalizes on local knowledge and insights for material screening, which can be difficult to obtain without access to regional data and information. Our analysis specifically focused on treatment technologies and efficiencies related to the removal of the following heavy metals: cadmium, copper, mercury, manganese, nickel, lead, and zinc. While aluminum and iron attenuation have also been investigated, we assigned these
metals less relevance due to their ubiquity and comparatively low toxic implications [36]. Collectively, this approach enabled us to synthesize what has been learned about the potential application of locally available and inexpensive materials for heavy metal attenuation, curate these studies based on material class and treatment promise and identify a subset of these materials for further study and application.

2. Discussion

2.1. Screening of Peruvian Materials

We identified 36 studies from southern Peru published within the time period considered (i.e., between 2012 and 2019), in which 29 new (i.e., globally never tested before) organic materials were assessed for the removal of heavy metals. These studies were performed under laboratory batch conditions, with a focus on regional and synthetic waters. The analyses were performed by considering the absorbent used (low-cost organic material) and its efficiency in the removal of the analyzed contaminant from water (only available in percent) using synthetic or regionally harvested waters. Collective results from the synthesis of these materials with additional published reports focused on availability in the developing world resulted in the curation of heavy metal removal performance for a total of approximately 200 different materials. These materials were broadly classified into four groups to coarsely reflect their source: (1) algae and seashells; (2) bacteria and fungi; (3) terrestrial plant-derived materials (fruits, leaves, peels, seeds, stems, shells, moss, and others); and (4) other agricultural and processing materials.

Studies that documented results in equilibrium \( (q_e) \) adsorbent loading (mg/g) and removal efficiency (% removal) were included in this international synthesis. While removal efficiencies are experimentally dependent on material mass, aqueous phase volume and contaminant concentrations, this approach enables a coarse screen for potentially promising materials and paths forward within the confines of these experimental caveats. Peruvian results were classified according to the efficiency of the material for metal removal (i.e., removal percent, as previously mentioned), sorting them using to the following criteria: high efficiency \( (X \geq 90\%) \), medium efficiency \( (70\% \leq X < 90\%) \), and low efficiency \( (X < 70\%) \), with “X” being the percentage of metal removal obtained. Peruvian and international studies were combined in the same tables (see Tables 1–4) by curating both equilibrium loading and percent removal, as has been done by others (e.g., [10,14,15,25]).
Table 1. Heavy metal removal potential of algae and seashells in the developing world, in mg/g or (% removal) (Peruvian studies in black color). SNS stands for “species not specified”.

| Absorbant               | Cd (II) | Cr (III) | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|-------------------------|---------|----------|---------|---------|---------|---------|---------|---------|---------|--------|
| **Algae**               |         |          |         |         |         |         |         |         |         |        |
| *Ascophyllum nodosum*   | 69.7    |          |         |         | 35.2    |         | 41.2    |         |         | [37]   |
| *Chaetomorpha linum*    | 58.6    |          |         |         |         |         |         |         |         | [38]   |
| *Chlorella sp.*         |         |          |         |         |         |         | (94)    |         |         | [39]   |
| *Chlorella vulgaris*    | 67.0    |          |         |         |         |         |         |         |         | [40]   |
| *Chondracanthus chamissoi* | (46)   |          |         |         |         |         |         |         |         | [41]   |
| *Chondrus crispus*      | 65.2    |          |         |         | 35.2    |         | 42.5    |         |         | [37]   |
| *Cladophora sp.*        |         |          | 14.5    |         |         |         |         |         |         | [42]   |
| *Codium vermilara*      | 21.4    |          |         |         | 12.9    |         | 21.6    |         |         | [37]   |
| *Ecklonia sp.*          |         |          | (60)    |         |         |         |         |         |         | [43]   |
| *Enterobacter sp.*      | 46.2    |          |         |         | 32.5    |         | 50.0    |         |         | [44]   |
| *Fucus vesiculosus*     |         |          |         |         |         | 42.6    |         |         |         | [45]   |
| *Gracilaria caudata*    |         |          |         |         |         |         | 45.0    |         |         | [46]   |
| *Gracilaria salicornia* | 19.6    |          |         |         |         |         |         |         |         | [38]   |
| *Laminaria japonica*    |         |          |         |         |         |         |         |         | 91.5    | [47]   |
| *Oedogonium hatei*      |         |          |         |         |         |         |         |         | 40.9    | [48]   |
| *Padina tetrastomatica* | 64.0    |          |         |         |         |         |         |         |         | [38]   |
| *Palmaria palmate*      |         |          |         |         |         |         |         |         | 33.8    | [45]   |
| *Pelvetia canalicula*   | 75.0    |          |         |         |         |         |         |         |         | [49]   |
| *Sargassum muticum*     |         |          |         |         |         |         |         |         | (70)    | [46]   |
| *Sargassum natans*      | 115.0   |          |         |         |         |         |         |         |         | [50]   |
| *Scenedesmus obliquus*  | (99)    |          |         |         |         |         |         |         | 140.0   | [51]   |
| *Spirogyra sp.*         |         |          |         |         |         |         |         |         | 133.3   | [52]   |
| *Spirogyra sp.*         |         |          |         |         |         |         |         |         |         | [53]   |
| Absorbant                                      | Cd (II) | Cr (III) | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|-----------------------------------------------|---------|----------|---------|---------|---------|---------|---------|---------|---------|--------|
| Spirulina platensis                          |         | (91)     |         |         |         |         |         |         |         | [54]   |
| Stoechospermum marginatum                    |         |          | 67.9    |         |         |         |         |         |         | [55]   |
| Ulva lactuca                                 |         |          |         | 35.7    |         |         |         |         |         | [56]   |
| Seashells                                    |         |          |         |         |         |         |         |         |         |        |
| Clam (Anadara inaequivalvis)                 |         |          |         |         | 330.0   | 621.0   |         |         |         | [58]   |
| Crab particles (Brachyura sp.)               |         |          |         |         | 244.0   |         |         |         |         | [59]   |
| Oyster (Crassostrea sp.)                     |         |          | 118.0   |         |         | 1591.0  | 564.0   |         |         | [60]   |
| Razor clam (Siliqua patula)                  |         |          |         |         | 501.0   | 657.0   | 553.0   |         |         | [60]   |
| Mixed Media                                  |         |          |         |         |         |         |         |         |         |        |
| Algae (Scenedesmus obliquus) and fungi (Wallemia sebi) | (100)   |          |         |         |         |         |         |         |         | [61]   |
| Seashells (Mussel Mytilidae sp.) and charcoal|         |          |         |         |         |         |         |         |         | [62]   |
| Seashells (SNS), eggshells, and activated charcoal | (95)    |          |         |         |         |         |         |         |         | [63]   |

Table 2. Heavy metal removal potential of bacteria and fungi in the developing world, in mg/g or (% removal) (Peruvian studies in black color). SNS stands for “species not specified”.

| Absorbant                     | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|-------------------------------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Bacteria                      |         |                        |         |         |         |         |         |         |         |        |
| Arthrobacter sp.              |         | 32.6                   |         |         |         |         |         |         |         | [64]   |
| Bacillus cereus               |         |                        |         |         | 44.4    |         |         | 66.6    |         | [65]   |
| Bacillus circulans            |         |                        |         |         |         |         |         |         | 34.5    | [66]   |
| Bacillus coagulans            |         |                        |         |         |         |         |         |         | 39.9    | [67]   |
| Absorbant                                | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|------------------------------------------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Bacillus licheniformis                   | (95)    |                        | (32)    |         |         |         |         |         |         | [69]   |
| Bacillus megaterium                      | 32.0    |                        |         |         |         |         |         |         |         | [67]   |
| Bacillus pumilus                         |         |                        |         |         |         |         |         |         | 28.1    | [70]   |
| Bacillus thuringiensis                   | 41.8 (16)|                       |         |         |         |         |         |         |         | [71]   |
| Escherichia coli                         | 1.5 (79)| 1.2 (100)              | 1.4 (74)|         |         |         |         |         |         | [72]   |
| Mucor rouxii                             | 8.5     |                        |         |         |         |         |         |         |         | [66]   |
| Pantoeea sp.                             | 52.0    |                        |         |         |         |         |         |         |         | [74]   |
| Pseudomonas aeruginosa PU21              | 57.4    |                        |         |         |         |         |         |         |         | [66]   |
| Pseudomonas fluorescens                  | 66.3    |                        |         |         |         |         |         |         |         | [75]   |
| Pseudomonas putida                       | 53.5    | 128.0                  |         |         |         |         |         |         |         | [76]   |
| Pseudomonas veronii 2E                   | 54 (47) | (35)                   |         |         |         |         |         |         | 180.4   | [66]   |
| Rizobium leguminosarum (var. Viciae)     | 135.3   |                        |         |         |         |         |         |         |         | [78]   |
| Trametes versicolor                      |         |                        |         |         |         |         |         |         | 140.9   | [79]   |
| **Fungi**                                |         |                        |         |         |         |         |         |         |         |        |
| Agaricus bisporus                        | 29.7    |                        |         |         |         |         |         |         | 33.8    | [80]   |
| Aspergillus flavus                       | 93.7    |                        |         |         |         |         |         |         |         | [81]   |
| Aspergillus niger                        | (58)    | 9.5 (34)               |         |         |         |         |         |         |         | [82]   |
| Aspergillus terreus                      |         |                        |         |         |         |         |         |         | 180 (90)| [84]   |
| Auricularia polytricha                   | 6.6     | 6.0                    |         |         |         |         |         |         | 6.1     | [85]   |
| Botrytis cinerea                         |         |                        |         |         |         |         |         |         | 13.0    | [86]   |
| Calocybe indica                          | 24.1    |                        |         |         |         |         |         |         | 23.4    | [80]   |
| Absorbant                                      | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|-----------------------------------------------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Cephalosporium aphidicola                     |         |                        |         |         |         |         | 36.9    |         |         | [86]   |
| Flammulina velutipes                          |         | 7.2                    | 7.9     |         |         |         |         | 6.3     |         | [85]   |
| Lentinus sajor-caju (free)                    |         |                        |         |         |         |         | 18.9    |         |         | [87]   |
| Lentinus sajor-caju (immobilized)             |         |                        |         |         |         |         | 32.3    |         |         | [87]   |
| Mucor rouxii (alive)                          | 8.5     |                        |         | 11.1    | 35.7    | 7.8     |         |         |         | [88]   |
| Mucor rouxii (dead)                           | 20.3    |                        |         | 20.5    | 53.8    | 53.9    |         |         |         | [88]   |
| Pencillium purpurogenum                       | 110.4   |                        | 70.4    |         |         |         |         | 252.8   |         | [89]   |
| Pencillium simpliccium                        | 52.5    |                        |         |         | 76.9    | 65.6    |         |         |         | [90]   |
| Penicillium sp.                               | (97) *  |                        |         |         |         |         |         |         |         | [91]   |
| Penicillium canescens                         | 102.7   |                        | 54.8    |         |         |         |         | 213.2   |         | [92]   |
| Penicillium chrysogenum                       |         |                        |         |         | 12.3    |         |         |         |         | [93]   |
| Penicillium citrinum                          |         |                        |         |         |         |         | 56.0    |         |         | [94]   |
| Penicillium digitatum                         | 3.5     |                        |         |         |         |         |         | 9.7     |         | [96]   |
| Phanerochaete chrysosporium                   |         |                        |         |         | 55.9    | 53.6    |         |         |         | [97]   |
| Pichia guilliermondii                         |         |                        |         | 20.0    |         |         |         |         |         | [99]   |
| Pleurotus eryngii                             | 3.4     | 2.8                    | 2.9     |         |         |         |         |         |         | [85]   |
| Pleurotus ostreatus                           | 10.8    | 8.1                    | 20.4    | 3.2     |         |         |         |         |         | [100]  |
| Pleurotus platypus                            | (21)    |                        | 4.5     | 3.4     | 5.1     |         |         |         |         | [85]   |
| Pycnoporus sanguineus                         |         |                        |         |         |         |         | 2.8     |         |         | [102]  |
| Rhizopus arrhizus                             | (23)    | 10.8 (36)              |         |         |         |         |         |         |         | [83]   |
| Pleurotus platypus                            | 35.0    |                        |         |         |         | 27.1    |         |         |         | [80]   |
| Pycnoporus sanguineus                         |         |                        |         |         |         |         | 2.8     |         |         | [102]  |
| Rhizopus arrhizus                             | 25.0    |                        |         |         |         |         |         |         |         | [50]   |
| Rhizopus arrhizus                             | 30.0    |                        |         |         |         |         |         |         |         | [94]   |
### Table 2. Cont.

| Absorbant                  | Cd (II) | Cr (III) or Cr Total | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|---------------------------|---------|----------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| *Saccharomyces cerevisiae*|         | 32.6                 | 46.3    | 270.3   |         |         |         |         |         | [103]  |
|                           | 1.0     |                      |         |         |         |         |         |         |         | [104]  |
|                           | 31.8    |                      |         |         |         |         |         |         |         | [105]  |
|                           |         | 11.4                 | 9.0     |         |         |         |         |         |         | [106]  |
|                           |         | (87)                 |         |         |         |         |         |         |         | [107]  |
| *Trametes versicolor*     |         | 11.3                 | 3.3     |         |         |         |         |         |         | [108]  |

**Mixed Media**

- Bacteria. (*Lactobacillus delbruckii* var. *Bulgaricus* and *Streptococcus thermophilus*)
- Fungi. (*Alternaria* sp., *Aspergillus* sp., *Pseudocamarosporium* sp., and *Penicillium* sp.)

### Table 3. Heavy metal removal potential using terrestrial plant-derived materials in the developing world, in mg/g or (% removal) (Peruvian studies in black color). SNS stands for “species not specified”.

| Absorbant                  | Cd (II) | Cr (III) or Cr Total | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|---------------------------|---------|----------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| **Fruits**                |         |                      |         |         |         |         |         |         |         |        |
| Quinoa (*Chenopodium quinoa*) |         | (55)                 |         |         |         |         |         |         |         | [113]  |
| Taro (*Colocasia esculenta*) |     |                      |         |         |         |         |         |         |         | [114]  |
| Tuya oriental (*Thuja orientalis*) |       |                      |         |         |         |         |         |         | 12.4    | [115]  |
| Apple (*Malus sp.*)        |         |                      |         |         |         |         |         |         | 10.8    | [116]  |
| Apricot (*Prunus armeniaca*) |         |                      |         |         |         |         |         |         | 101.0   | [117]  |
| Absorbant                  | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|---------------------------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| **Leaves**                |         |                        |         |         |         |         |         |         |         |        |
| Amaltas (Cassia fistula)  | 4.5     |                        |         |         |         |         |         |         |         | [118]  |
| Cactus (Cumulopuntia unguispsina) | (97) | (96)                  |         |         |         |         |         |         |         | [119]  |
| Cactus (SNS)              | (55)    | (20)                   |         |         |         |         |         |         |         | [120]  |
| Mangrove (Rhizophora mangle L.) | 6.5  | 5.7                  |         |         |         |         |         |         |         | [114]  |
| Neem (Azadirachta indica) | 16.0    |                        |         |         |         |         |         |         |         | [121]  |
| Pineapple (Ananas comosus) | 9.3     |                        |         |         |         |         |         |         |         | [122]  |
| **Peels**                 |         |                        |         |         |         |         |         |         |         |        |
| Avocado (Persea americana)| (88)    |                        |         |         |         |         |         |         |         | [124]  |
| Banana (Musa paradisiaca) |         | (100)                  |         |         |         |         |         |         |         | [125]  |
| Banana (Musa sp.)         |         | 34.1                   | 52.4    | 54.4    | 25.9    | 21.9    |         |         |         | [126]  |
|                           |         | 4.8                    | 6.9     | 7.9     | 5.8     |         |         |         |         | [127]  |
|                           |         | 7.4                    |         |         |         |         |         |         |         | [128]  |
|                           |         | (95)                   |         |         |         |         |         |         |         | [129]  |
| Banana, cortex (Musa sp.) | 195.0   | 240.0                  |         |         |         |         |         |         |         | [19]   |
| Cassava (Manihot esculenta)| 119.6  | 127.3                  |         |         |         |         |         |         |         | [130]  |
|                           |         |                        |         |         |         |         |         |         |         | [131]  |
| Chestnut (Bertholletia excelsa) |         | (59)                  |         |         |         |         |         |         |         | [132]  |
| Sweet lemon (Citrus limetta) |         | 250.0                  |         |         |         |         |         |         |         | [133]  |
| Clementine, peel’s pectin (Citrus reticulata) |         | (72)                  |         |         |         |         |         |         |         | [134]  |
| Cucumber (Cucumis sativus) |         | (87)                   |         |         |         |         |         |         |         | [135]  |
| Grapefruit (Citrus paradisi) | 42.1  | 46.1                 |         |         |         |         |         |         |         | [136]  |
| Kiwi, cortex (Actinidia delicosa) | 470.0  | 375.0                 |         |         |         |         |         |         |         | [19]   |
| Lemon (Citrus limon)      | 54.6    | (12) *                | 70.9    | 80.0    | 37.9    | 27.9    |         |         |         | [126]  |
| Lemon, peel’s pectin (Citrus x limon) |         |                        |         |         |         |         |         |         |         | [134]  |
| Absorbant                     | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|------------------------------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Orange (Citrus senensis)     |         |                        |         |         |         |         |         |         |         |        |
|                              |         |                        |         |         |         |         |         |         |         |        |
|                              |         | (60)                   |         |         |         |         |         |         |         |        |
|                              | 41.8    | 63.3                   | 81.3    | 27.1    | 24.1    |         |         |         |         | [126]  |
|                              |         | 1.8                    | 6.0     | 7.8     | 5.3     |         |         |         |         | [127]  |
|                              | 293.0   |                       | 162.0   | 476.0   |         |         |         |         |         | [139]  |
|                              |         |                        |         |         |         |         |         |         |         | [140]  |
|                              |         |                        |         |         |         |         |         |         |         | [141]  |
| Orange, modified (Citrus senensis) |         |                        |         |         |         |         |         |         |         | [142]  |
| Orange, peel’s pectin (Citrus x sinensis) | (18) * | 289.0 | | | | | | | | [143] |
| Pomegranate (Punica granatum) |         |                        |         |         |         |         |         |         |         | [144]  |
| Potatoe (SNS)                |         | 3.3                    |         |         |         |         |         |         |         | [145]  |
| Prickly pear (Opuntia ficus, var. Indica) | (99) | | | | | | | | | [146] |
| Tangerine, cortex (Citrus reticulata) | 450.0 | 350.0 | | | | | | | | [19] |
| Walnut (Bertholletia excelsa) |         | (38)                   |         |         |         |         |         |         |         | [132]  |
| Seeds                        |         |                        |         |         |         |         |         |         |         |        |
| Date (Phoenix dactylifera)    | 39.5    | 35.9                   |         |         |         |         |         |         |         | [147]  |
| Papaya arequipeña (Vasconcellea pubescens) | (80) | (78) | | | | | | | | [148] |
| Almond (Prunus sp.)          |         | (60)                   | 10.2 (24) |         |         |         |         |         |         | [120]  |
| Coffee (Canephora sp.)       | 39.5    | 31.2                   | 11.0    | 19.5    | 13.4    |         |         |         |         | [149]  |
| Stems                        |         |                        |         |         |         |         |         |         |         |        |
| Rose (Rosa sp.)              |         | (41)                   |         |         |         |         |         |         |         | [150]  |
| Grape tree (Vitis sp.)        |         |                        |         |         |         |         |         |         | 10.1    | [152]  |
| Shells                       |         |                        |         |         |         |         |         |         |         |        |
| Absorbant                          | Cd (II) | Cr (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|------------------------------------|---------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Cashew nut (*Anacardium occidentale*) |         |         |                        |         |         |         |         | 18.9    |         |         | [153]  |
| Cocoa (*Theobroma cacao*)           | 0.2     | 0.2     |                        | 0.5     | 0.1     | 0.2     | 5.2     | 0.0     |         |         | [155]  |
| Coconut (*Cocos sp.*)               |         |         |                        |         |         |         | 18.7    |         |         | 19.9    | [121]  |
| Coconut, green (*Cocos nucifera*)  | (99)    | (90)    | (86)                   |         |         |         |         |         |         |         | [156]  |
| Dye groundnut                       |         |         |                        |         |         |         |         | 7.5     |         |         | [157]  |
| Groundnut (*Arachis hypogaea*)      |         |         |                        |         |         |         |         | 4.5     | 3.8     | 7.6     | [157]  |
| Hazelnut (*Corylus sp.*)            |         |         |                        |         |         |         |         | 58.3    |         |         | [158]  |
| Nutshells (SNS)                     |         |         |                        |         |         |         |         | 19.4    |         |         | [159]  |
| Peanut (*Arachis hypogaea*)         |         |         |                        |         |         |         |         | 27.9    | 25.4    |         | [22]   |
| Walnut (*Juglans sp.*)              |         |         |                        |         |         |         |         |         |         | 1.5     | [160]  |
| Wheat                              |         |         |                        |         |         |         |         | 10.8    | (99)    |         | [161]  |
| **Moss**                            |         |         |                        |         |         |         |         |         |         |         |        |
| Moss (*Fontinalis antipyretica*)    | 28.0    |         |                        |         |         |         |         |         |         | 15.0   | [162]  |
| Moss (*Hylocomium splendens*)       | 32.5    | 42.1    |                        |         |         |         |         |         |         |         | [163]  |
| Moss (Irish peat)                   | 17.6    |         |                        |         |         |         |         |         |         | 14.5   | [164]  |
| **Other Plant-Derived Materials**   |         |         |                        |         |         |         |         |         |         |         |        |
| Amicon regenerated cellulose       |         |         |                        |         |         |         |         |         |         |         | (99)   | [165]  |
| Apricot stone (*Prunus americana*)  |         |         |                        |         |         |         |         |         |         |         | (93)   | [166]  |
| Bagasse, sugar cane (SA-SC)         |         |         |                        |         |         |         |         |         |         |         | (96)   | [167]  |
| Bagasse, sugar cane (*Saccharum officinarum*) |         |         |                        |         |         |         |         |         |         |         | (96)   | [168]  |
|                                    |         |         |                        |         |         |         |         |         |         | 87.0   | [140]  |
|                                    |         |         |                        |         |         |         |         |         |         | 2.2    | [170]  |
| Absorbant                        | Cd (II) | Cr (III) or Cr Total | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|---------------------------------|---------|----------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Bagasse, sugar cane flyash      | 6.2     |                      | 6.5     |         |         |         |         |         |         | [171]  |
| (Saccharum officinarum)         |         |                      |         |         |         |         |         |         |         |        |
| Bark (Abies alba)               |         |                      |         |         |         |         |         |         |         | [172]  |
| Bark (Acer rubrum)              |         |                      |         |         |         |         |         |         |         | [173]  |
| Bark (Azadirachta indica)       |         |                      |         |         |         |         |         |         |         | [174]  |
| Bark (Hardwickia binata)        |         |                      |         |         |         |         |         |         |         | [175]  |
| Bark (Lagerstroemia speciosa)   | 24.4    | 11.3                 |         |         |         |         |         |         |         | [176]  |
| Bark (Moringa oleifera)         |         | (93)                 |         |         |         |         |         |         |         | [177]  |
| Bark (Pausinystalia johimbe)    |         | (100)                |         |         |         |         |         |         |         | [178]  |
| Bark (Pinus nigra)              | 5.7     | 13.5                 | 6.3     |         |         |         |         |         |         | [179]  |
| Bark (Pinus palustris)          |         |                      |         |         |         |         |         |         |         | (73)   |
| Bark (Pinus radiata)            |         | (98)                 |         |         |         |         |         |         |         | [180]  |
| Bark (Pinus sp.)                | 8.2     | (69)                 |         |         |         |         |         |         |         | [182]  |
| Bark (Sequoia sempervirens)     | (97)    | (97)                 |         |         |         |         |         |         |         | [183]  |
| Bark (Techtona grandis)         |         | (93)                 |         |         |         |         |         |         |         | (99)   |
| Bark (Terminalia tomentosa)     | (94)    | (68)                 |         |         |         |         |         |         |         | [185]  |
| Bark (Tsuga heterophylla)       |         | (99)                 |         |         |         |         |         |         |         | [186]  |
| Bran, barley (Hordeum vulgare)  |         |                      |         |         |         |         |         |         |         | (59)   |
| Bran, rice (Oryza sp.)          |         |                      |         |         |         |         |         |         |         | [121]  |
| Cellulose bearing schiff        | 12.3    |                      | 21.0    |         |         |         |         |         |         | [122]  |
| Coagulant, sentry plant (Agave americana) | 87.0    | 85.0                |         |         |         |         |         |         |         | [188]  |
| Cork (Pausinystalia johimbe)    |         | (85)                 | (91)    |         |         |         |         |         |         | [175]  |
| Cork, olive (Olea europea)      |         | (67)                 |         |         |         |         |         |         |         | [189]  |
Table 3. Cont.

| Absorbant | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|-----------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Corncob (Zea mays) | 5.1     | (91)                   |         |         |         |         |         |         |         | [190]  |
| Corncob (Zea mays) (oxidized) | 55.7    |                       |         |         |         |         |         |         |         | [191]  |
| Endocarp, olive (Olea europea) | (60)    | (89)                   |         |         |         |         |         |         |         | [192]  |
| Fiber, ramie (Boehmeria nivea) | 159.1   | 273.8                  |         |         |         |         |         |         |         | [193]  |
| Hull, peanut (Arachis hypogaea) | 21.3    | 12.0                    |         |         |         |         |         |         |         | [194]  |
| Hull, almond (SNS) |         | 39.8                   |         |         |         |         |         |         |         | [195]  |
| Husk, coconut coir (Cocos nucifera) | (75) | (80)                   |         |         |         |         |         |         |         | [197]  |
| Husk, peanut (Arachis hypogaea) | 7.7     | 10.2                   | 5.5     | 58.0    | 8.1    |         |         |         |         | [198]  |
| Husk, rice (Oryza sp.) | 16.6    | 11.4                   | 10.9    | 36.1    |         | 5.5     | 58.0    | 8.1     |         | [199]  |
| Husk, rice (Oryza sp.) |         | (77)                   |         |         |         |         |         |         |         | [200]  |
| Husk, rice (Oryza sp.) |         | 17.9                   |         |         |         |         |         |         |         | [201]  |
| Husk, rice (Oryza sp.) |         | (99)                   |         |         |         |         |         |         |         | [202]  |
| Leaf powder, neem (Azadirachta indica) | 6.6     | 4.0                    | 9.6     |         |         |         |         |         |         | [203]  |
| Leaf powder, neem (Azadirachta indica) |         | (93)                   |         |         |         |         |         |         |         | [204]  |
| Maize cobs (SNS) |         | (99)                   |         |         |         |         |         |         |         | [201]  |
| Mat, reed (Cannomois virgata) | 7.2     | 1.7                    |         |         |         |         |         |         |         | [114]  |
| Oil cake, neem (Azadirachta indica) | 11.8    | 9.4                    |         |         |         |         |         |         |         | [205]  |
| Okra cellulosic (Abelmoschus esculentus) | 121.5   | 72.7                   |         |         |         |         |         |         |         | [206]  |
| Peach stone (Prunus sp.) |         | (97)                   |         |         |         |         |         |         |         | [166]  |
| Peanut skins (SNS) |         | 820.0                  |         |         |         |         |         |         |         | [207]  |
| Pine needles (Pinus sp.) | (79)    | 21.5 (43)              |         |         |         |         |         |         |         | [120]  |
| Absorbant                        | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|---------------------------------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Pulp, sugar beet (SNS)          |         |                        | 28.5    |         |         |         |         |         |         | [208]  |
| Roots, hyacinth (Hyacinthus orientalis) |         |                        | 15.3    |         |         |         |         |         |         | [121]  |
| Sawdust (Cryptomeria japonica)  | (75)    |                        | 21.8    |         |         |         |         |         |         | [209]  |
| Sawdust (Eucalyptus sp.)        | (93)    |                        |         |         |         | (99)    |         |         |         | [201]  |
| Sawdust (SNS)                   |         |                        |         | 1.0     | 1.0     |         |         |         |         | [210]  |
| Sawdust (Ziziphus mauritiana)   |         |                        | 3.7 (99)|         |         |         |         |         |         | [212]  |
| Sawdust, beech (Fagus sp.)      |         |                        | 4.5     | 4.0     | 2.0     |         |         |         |         | [213]  |
| Sawdust, fir-wood (Abies sp.)   | (100)   |                        |         | (100)   |         |         |         |         |         | [17]   |
| Sawdust, maple (SNS)            |         |                        | 0.3     |         |         |         |         |         |         | [157]  |
| Sawdust, meranti (Shorea sp.)   |         |                        | 37.9    | 32.1    | 36.0    | 34.2    |         |         |         | [214]  |
| Sawdust, neem (Azadirachta indica) |         |                        | (95)    |         |         |         |         |         |         | [177]  |
| Sawdust, papaya wood (Carica papaya) | (98) | (95)                   | (67)    |         |         |         |         |         |         | [215]  |
| Sawdust, poplar (Populus sp.)   | (95)    |                        | 5.5     | 6.6     | 21.1    |         |         |         |         | [198]  |
| Sawdust, teakwood (Tectona grandis) |         |                        | 4.9     | 8.1     | 11.0    |         |         |         |         | [216]  |
| Straw, barley (Hordeum vulgare) |         |                        | 4.6     |         | 23.2    |         |         |         |         | [217]  |
| Straw, rice (Oryza sp.)         |         |                        | 54.5    |         |         |         |         |         |         | [121]  |
| Straw, rice (SNS)               |         |                        | 18.4    |         |         |         |         |         |         | [122]  |
| Straw, wheat (SNS)              |         |                        | 280.0   |         |         |         |         |         |         | [207]  |
| Straw, wheat (Triticum aestivum)|         |                        | 4.9     | 1.9     |         |         |         |         |         | [219]  |
### Table 3. Cont.

| Absorbant                                      | Cd (II) | Cr (III) or Cr Total * | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|------------------------------------------------|---------|------------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| Tree fern (Cyatheales sp.)                     | 10.6    | 39.8                   | 7.6     |         |         |         |         |         |         | [220]  |
| Water hyacinth (Eichhornia crassipes)          | 6.6     | 0.3                    |         |         |         |         |         |         |         | [114]  |
| Water lily (Nymphaea sp.)                      | 6.1     | 5.1                    |         |         |         |         |         |         |         | [114]  |
| Wood, juniper (Juniperus sp.)                  | 3.2     |                        |         |         |         |         |         |         |         | [221]  |

**Mixed Media**

| Peels. Four Peruvian potatoe species (Solanum sp.) | (98)    |                        |         |         |         |         |         |         |         | [222]  |
| Corn husk (Zea mays) and rice husk (Oryza sativa) | (95)    |                        |         |         |         |         |         |         |         | [223]  |
| Sawdust from oak (Quercus sp.) and fir-wood (Fagus sp.) | (98)    |                        |         |         |         |         |         |         |         | [17]   |

### Table 4. Heavy metal removal potential using other agricultural and processing materials in the developing world, in mg/g or (% removal) (Peruvian studies in black color). SNS stands for “species not specified”.

| Absorbant                                      | Cd (II) | Cr (III) | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|------------------------------------------------|---------|----------|---------|---------|---------|---------|---------|---------|---------|--------|
| Baby’s breath (Gypsophila elegans)             |         |          |         | 12.4    | 5.2     | 6.5     |         |         |         | [224]  |
| Barely straw (Rosser)                          |         |          |         |         | 35.8    |         |         |         |         | [218]  |
| Cabbage (Brassica oleracea var. capitata)      |         |          |         | 32.7    |         |         |         |         |         | [17]   |
| Cardboard                                      | (95)    |          |         |         |         |         |         |         |         | [17]   |
| Carrot (Daucus carota L.)                      |         |          |         |         |         |         |         |         |         | [226]  |
| Carrot (SNS)                                   | 47.6    |          |         |         |         |         |         |         |         | [227]  |
| Cauliflower (Brassica oleracea var. botrytis)  |         |          |         |         |         |         |         |         |         | [225]  |
| Coconut milk processing (Cocos sp.)            | 500.0   |          |         |         |         |         |         |         |         | [228]  |
| Coir pith (SNS)                                |         |          |         |         |         |         |         |         | 9.5     | [229]  |
| Coir pith (SNS), modified                      |         |          |         |         |         |         |         |         | 38.9    | [229]  |
Table 4. Cont.

| Absorbant                                         | Cd (II) | Cr (III) | Cr (VI) | Cu (II) | Hg (II) | Mn (VI) | Ni (II) | Pb (II) | Zn (II) | Source |
|---------------------------------------------------|---------|----------|---------|---------|---------|---------|---------|---------|---------|--------|
| Dung, cow (*Bos taurus*)                          |         |          | (99)    |         |         |         |         |         |         | [230]  |
| Eggshells (SNS)                                   |         |          | (89)    |         |         |         |         |         |         | [231]  |
| Feathers, Chicken (SNS)                           |         |          |         |         | 24.4    |         |         |         |         | [207]  |
| Green bean (*Phaseolus vulgaris*)                  | (88)    |          |         |         |         |         |         |         |         | [232]  |
| Hemp (*Cannabis sp.*)                              |         |          |         |         |         |         |         |         | 242.0   | [233]  |
| Larch tannin resin (*Larix gmelinii* Rupr.)       |         |          |         |         |         |         |         |         |         | [234]  |
| Organoalkoxysilane-grafted lignocellulose         | (90)    |          |         |         |         |         |         |         |         | [235]  |
| Paper mill                                        | 14.8    | 13.9     |         | 13.7    | 14.1    |         |         |         |         | [236]  |
| Pistachio hull (*Pistacia vera*)                   |         |          |         |         | 116.0   |         |         |         |         | [237]  |
| Rice bran (SNS)                                   |         |          |         |         | 27.8    |         |         |         |         | [238]  |
| Sour orange (SNS)                                 |         |          |         |         | 21.7    |         |         |         |         | [239]  |
| Soybean hulls (SNS)                               |         |          |         |         | 154.9   |         |         |         |         | [240]  |
| Sporopollenin (*Lycopodium clavatum*)             | 1.6     | 1.2      |         |         |         | 90.9    | 166.7   |         |         | [9]    |
|                                                    |         |          |         |         |         | 13.8    | 12.2    |         |         | [241]  |
|                                                    |         |          |         |         |         | 43.2    |         |         |         | [242]  |
| Tea (*Camellia sinensis*)                         |         |          |         |         |         |         |         |         |         | [243]  |
|                                                    |         |          |         |         |         |         |         |         |         | [244]  |
|                                                    |         |          |         |         |         |         |         |         |         | [245]  |
|                                                    |         |          |         |         |         |         |         |         |         | [246]  |
| Tea (SNS)                                         |         |          |         |         |         |         |         |         |         | [160]  |
| Waste pomace of olive oil factory (WPOOF)         |         |          |         |         |         |         |         |         |         | [247]  |
| Wool, sheep (*Ovis aries*)                        |         |          |         |         |         |         |         |         |         | [248]  |
|                                                    |         |          |         |         |         | (58)    | 41.2 (69)|         |         | [120]  |
| Wool, sheep (SNS)                                 |         |          |         |         |         |         |         |         |         | [207]  |
| Mixed Media                                       |         |          |         |         |         |         |         |         |         | [249]  |
| Kraft lignin from poplar and beech wood (SNS)     |         |          |         |         |         |         |         |         | 580.0   |         |
2.2. Most Promising Peruvian Materials

Of the 29 newly identified organic materials from southern Peru, 19 were able to remove more than 90% of the targeted metals from experimental waters. Waste products and other abundant and inexpensive organic materials such as those compiled here could be applied toward metal removal of river-derived waters prior to agricultural irrigation. This is important given their potential for bioaccumulation in commercial agricultural products and implications for human consumption and commercial export [250]. Materials could also be applied to the treatment of mining impacted waters associated with small-scale informal mining operations in the region. Applications using what would otherwise be waste materials could limit their direct introduction to landfills but also comes with a tradeoff of the need to subsequently dispose of metal-contaminated materials, treatment and subsequent regeneration as explored later in the manuscript.

While the tables below enable interpretation across elements, here we present Pb, Cd, and Cr as examples. Among the best Peruvian adsorbents (in terms of removal efficiency), green algae were capable of reducing metal concentrations of Cd below detection limits. Positive results were also obtained when combining different materials into a mixed adsorbent media, such as different species of fungi (for the removal of Cr and Pb), as well as fungi mixed with microalgae (Pb). Tested materials that showed almost complete metal removal (99%) were cow dung (Pb) and Peruvian prickly pear (Pb). Other efficient materials worth mentioning based on their high removal efficiency are baby’s breath (Pb), sawdust from Eucalyptus (Cr), Peruvian cactus (Cd), Green bean (Pb), and rose stems (Pb), although, similar to the above, mixed materials also showed high efficiencies, highlighting four species of Peruvian potatoes (Cr). Peruvian materials that showed particularly low capacity for metal removal were walnut peel (Pb), chestnut peel (Pb), olive endocarp (Cr), quinoa (Cr), and rose stems (Cd), as shown in Tables 1–4. Table A1 provides removal capacities for comparatively less toxic aluminum and iron.

In addition to the above, some materials exhibited specific selectivity for different metals. For instance, data from a single study on avocado peels (Persea americana) indicated Al removal to below detection levels but only 88% removal of Mn (Tables 3 and A1). Similarly, certain algal species exhibited high selectivity such as Scenedesmus obliquus, which removed nearly 100% of Cd while others such as Chondracanthus chamissoi removed less than 50% of introduced Cu (Table 1). A mixture of these adsorbents, therefore, may allow for the removal of a broad range of heavy metals.

Along with removal efficiency, there are a number of additional considerations for selecting organic materials as a treatment technology, including (1) availability in large quantities; (2) the costs of large-scale production; (3) the potential to create other environmental problems; and (4) the social and cultural “fit” of the material and its associated technologies. Out of the 19 Peruvian materials (including those that were tested in combination with other materials) that showed more than 90% removal efficiency, these constraints limit real-world applicability of a number of organic materials. Scenedesmus obliquus (Table 1), for example, was able to remove 99% of Cd [51], but this green alga mostly occurs as a unique population in plankton [251], making it difficult to harvest in sufficiently large quantities for water treatment applications. This in turn limits applications such as combining these algae with the fungi Wallemia sebi that was shown to remove nearly all Pb from water [61]. Certain seashells, however, are locally abundant near the coast (e.g., [252]) and have shown excellent Hg and Cu removal efficiencies when combined with similarly abundant and inexpensive charcoal [62] and eggshells [63].

Ref [91] used Penicillium to remove Cr from water, reaching below detection levels (Table 2). This genus is ubiquitous and abundant in soils [253] but also produces antibiotics that while useful in biomedical applications, could challenge its application in this context [254] necessitating sterilization, strain selection or genetic engineering to limit antibiotic release. Similarly, the fungal genera Alternaria and Aspergillus are abundant in soils [255] and used to supply many industrial processes [256]. Penicillium and Pseudocamarosporium are abundant in wheat crops [257], highlighting the potential of a combination of these four fungal genera (Alternaria, Aspergillus, Penicillium, and Pseudocamarosporium)
for removing Cr and Pb from waters [112]. Despite the potential applications of these fungi, production and extraction costs should be taken into consideration, as well as any potential effects on downstream aquatic ecosystems.

Even though [119] obtained excellent results using *Cumulopuntia unguispina* on the removal of Cd and Mn from water (Table 3), this cactus is a species that exists only in southern Peru [258], limiting its sustainable extrapolation for water treatment in other regions. However, the species is commonly used for local production in agroforestry systems (marmalades, nectars, alcoholic beverages, shampoo, slope stabilization, etc.), making it potentially feasible for regional water treatment projects particularly if residual wastes remain from those applications. Conversely, *Opuntia ficus* var. *Indica* (Peruvian prickly pear) showed great capacity to remove Pb [146]. It is abundant in Peru and elsewhere and used for industrial purposes around the globe [259], suggesting it holds higher promise for future large-scale water treatment projects. Similarly, rose stems (*Rosa* sp.) [150] and *Agave americana* [188] are also abundant on the continent and represent promising materials for Pb removal. Wood processing-derived materials such as sawdust from *Eucalyptus* sp. [209] may also be used in future water treatment projects to remove Cr, since they can be obtained in large quantities. Analogously, locally available mixed media made of peels from four Peruvian potato species (*Solanum* sp.) hold promise to remove Cr [222]. More globally, a combination of ubiquitous staple crop residuals such as corn husks (*Zea mays*) and rice husks (*Oryza sativa*) hold promise as abundant staples that also facilitate effective metal removal with complementary treatment attributes (Table 3).

*Gypsophila elegans* is an ornamental plant species that is found in many countries and has been found to remove Pb from water [260] though it has limited availability in southern Peru [224]. Cow dung (*Bos taurus*) (Table 4) showed excellent results when used to remove Pb from water [230], and it is an abundant material worldwide. However, special considerations must be taken, as it could create sanitary and ecological problems depending upon its downstream utilization and mandates for disinfection much as is implemented for municipal wastewater. In addition, public perceptions should be considered in conjunction with treatment and reuse to proactively address challenges that might be encountered in terms of impacts to crops and the potential proliferation of pathogens (e.g., [261]). As an example of food processing wastes, green bean residuals (*Phaseolus vulgaris*) hold promise for Pb removal from water in large-scale projects [232] depending on the local availability of this material.

2.3. International Analysis

These findings build on prior studies focused on materials available in southern Peru (e.g., [262,263]) and worldwide, as well as the continued identification of new materials that can be used to remove metals from water (e.g., [264]). Results from this analysis (a total of 203 studies; 36 Peruvian and 167 international) provide a synthesis and screening tool that can inform future studies and further inquiries into candidate materials to more effectively triage initial approaches. Heavy metal removal from water is affected by various water quality parameters such as organic matter, pH, ionic strength, contact time, total reactive sites and temperature (e.g., [8–10,25]). With these variables in mind, Peruvian results which are based on removal efficiency and not equilibrium loading or adsorption capacity can complement worldwide efforts. Collectively, this can provide a triage to inform future studies of promising materials as well as eliminate repetition of materials with limited potential. As shown in Tables 1–4, we propose that these different results can be binned for larger insights. Collectively, we have identified 12 new materials (detailed below) that could be used in large-scale water treatment projects to remove target heavy metals.

The present analysis of low cost organic materials used in southern Peru builds upon the results from earlier reviews (e.g., [14,25–27]), and other independent studies, expanding the state-of-the-art list from 185 known materials to 197, which is a 6% increase to the current knowledge on this topic. Promising synergies of high removal efficiency and large-scale applicability were identified including: two seashell-based mixed media (Table 1); one fungus and a mix of four more fungi (Table 2); three new plant species (Peruvian cactus, Peruvian prickly pear, and rose stems), peels from four Peruvian
potatoes, lignocellulose-based sorbants such as sawdust, corn and rice husk (Table 3); cow dung and green bean waste (Table 4); and avocado peels (Table A1). Additionally, new metals were tested in Peru with already documented materials, as is the case of Salas and Sarcco (2017) who obtained positive results using orange peels (*Citrus senensis*) to remove Fe from waters. This material demonstrated past promise for Cd, Cr, Cu, Ni, Pb, and Zn (e.g., [126,127,139–142]) (Tables 3 and A1). While this tabulation enables the reader to triage and bin materials, it also highlights variability between studies and the need for more consistent protocols to enable future screening studies. For instance, the sorption of Cd onto *Escherichia coli* was reported as 51% by [73] while [72] obtained 79% in Portugal. Similarly, Ref. [138] removed 60% of Cu using orange peels, while [142] was able to remove 92% of the metal from regional waters in India.

2.4. Adsorption Isotherms for Promising Materials

Meta-analyses often suffer from inconsistencies in both testing methods and reporting standards. Of particular note, the curated studies expressed results in terms of both equilibrium solid phase concentration (mg/g) and removal efficiency (%). Unfortunately, these expression measures of adsorption efficiency can only be directly compared if all operating conditions are identical, which they were not. The initial adsorbent concentration, ionic strength, contact time, and adsorbent dose all can have an effect on heavy metals removal through adsorption (e.g., [11,265]). The pH of the water source similarly impacts adsorption capacity and solubility [266] and kinetics of mass transfer are impacted by temperature (e.g., [267]).

A conceptual framework for comparison is provided by an adsorption isotherm model such as Langmuir (non-linear form shown as Equation (1)) to yield coefficients that can be used to assess the characteristics and effectiveness of different adsorbents [268].

\[ q_e = \frac{q_m K_L C_e}{1 + K_L C_e} \]  

*Equation (1)*

Where \( C_e \) represents the concentration of adsorbate at equilibrium (mg/L); \( q_e \) is the adsorption capacity at equilibrium; \( q_m \) is maximum adsorption capacity (mg/g); and \( K_L \) is the Langmuir constant related to adsorption capacity (mg/g). With an underlying assumption of monolayer coverage, this can be correlated with variations of the surface characteristics of the adsorbent (e.g., surface area per mass adsorbent, porosity) where large surface areas and pore volumes will result in higher adsorption capacity. The maximum adsorption capacity can be experimentally derived using different contaminant and adsorbent concentrations and fitting with either non-linear or linear forms of the Langmuir model. Recent research has indicated that data fitting is best performed with the non-linear Langmuir model (Equation (1)), as linear model fits may result in model parameter error [269]. Ideally, maximum adsorption capacity should be reported together with the Langmuir constant so that solid phase sorbate concentration and removal efficiency can be estimated for a given treatment application.

While more empirical, Freundlich isotherms are better suited to heterogeneous materials and tends to fit a wider variety of adsorption isotherm data (e.g., [270]). The Freundlich isotherm model is shown as Equation (2) below, where \( K_F \) is the Freundlich adsorption capacity parameter (L/g) and \( 1/n \) is the Freundlich adsorption intensity parameter (unitless; [270]).

\[ q_e = K_F C_e^{\frac{1}{n}} \]  

*Equation (2)*

For purposes of comparing different adsorbents for a given heavy metal, the authors recommend future research in the region to establish isotherms for a subset of the promising materials identified earlier such as sawdust, rice and corn husks. This is needed to understand the role of environmental conditions and regional water properties (pH, temperature, ionic strength, etc.), as well as active sites and capacities. Some of the identified Peruvian materials have been tested elsewhere in the developing world, such as seaweed (Table 1), fungi and bacteria (Table 2), peels from banana and orange, sawdust
(Table 3), and sheep wool (Table 4). Unfortunately, extrapolation is challenging due to variables in reporting convention, environmental conditions, and target metals.

2.5. Considerations of Material Feasibility and Applications in Water Treatment

In addition to material applications to water treatment, it is also important to consider the context in which this might be applied. The bacterium *E. coli* is readily studied in axenic cultures as a model laboratory organism and its capacity for metal sorption is important for fundamental study as well as applications (e.g., [72]). However, it is an enteric bacterium that includes pathogenic strains that have played prominent roles in food contamination and hence could be problematic in water treatment applications. Analogous concerns about the proliferation of pathogens can be raised for materials such as cow dung [230] and fungi [91,112]. Downstream disinfection could counter such adverse effects but would add complexity and cost that could limit adoption. Public perceptions of water treated with such materials could pose further challenges. On the other hand, non-potable uses for the treated water such as irrigation or mining processes could circumvent needs for disinfection. Increasing water availability for these applications will also decrease stress on potable resources which could increase adoption.

The regeneration and potential recovery of heavy metals from adsorbent materials is an important factor that influences material and disposal costs [271]. Although desorption and adsorbent regeneration has been well studied for commercial materials such as activated carbon and ion-exchange resin, the regeneration of the types of materials highlighted in this review have received much less attention [272]. A recent review [271] evaluated the literature on regenerating a wide range of adsorbent materials with a secondary focus on recovery of metals for recycling and fate of spent adsorbents. They concluded that more research is needed to evaluate the best regeneration methods for specific adsorbents, methods for recovering metals from regenerant solutions, and options for safely disposing of spent adsorbents. This is particularly applicable for the less studied, novel organic materials curated here highlighting the need to quantify and assess material regeneration, disposal, life cycle, and opportunities for economic metal recovery in conjunction with treatment efficacy.

Evaluation of materials prior to treatment applications should additionally include quantification of released constituents that could impact downstream use of the waters. The lifespan and breakdown of organic substances during treatment applications needs to be quantified to determine if adsorption capacity decays over time (e.g., [270]). Organic breakdown during treatment applications could result in the release of nitrogen, phosphorous and organic carbon that could contribute to eutrophication and increased oxygen consumption [273,274]. While this release could present a new set of environmental pressures, it could also provide opportunities if the water is used for applications such as agricultural irrigation, where the presence of introduced nutrients could enhance system productivity (e.g., [275]). In another vein, the decay and fermentation of organic substrates can sustain biogenic sulfide production in sulfate rich waters and in turn support passive treatment applications such as sulfate reducing bioreactors. In these systems, a combination of more labile and recalcitrant substrates such as alfalfa coupled to woodchips can sustain long-term immobilization of metal sulfides over a timeframe of years to decades [276,277]. Whether sorbed or precipitated, there are important and of yet unanswered questions associated with treatment lifespan as well as material disposal of heavy metal contaminated materials.

3. Conclusions and Recommendations

As water scarcity continues to increase in southern Peru (as well as other areas in Latin America) [278], it is important to investigate regionally abundant, low-cost materials that can be applied towards heavy metals removal. With limited water resources and projections of future scarcity, it is important to treat and reclaim supplies that have been impacted by natural and anthropogenic metal contamination. Regional studies have reported high metal content in locally grown food products in southern Peru (e.g., [250]), which highlight the need for cost-effective materials for metal removal...
in association with agricultural production. Water supply and quality have been the source of social conflicts in the region, often pitting mining and agriculture against each other (e.g., [279]). Low-cost remediation approaches could help promote coexistence between sectors. This benefit could extend to the artisanal and small-scale mining sector, which has not so far been a source of major conflict in southern Peru (e.g., [280]) by providing a potentially cost-effective, small scale treatment application using waste or inexpensive local materials as a mechanism to reduce the likelihood of future conflicts.

For the new materials, such as plant and food wastes, that hold higher promise, there are associated variables that need further consideration such as their availability, mass demands for water treatment, acquisition/processing cost, ability to integrate into treatment schemes, environmental effects, and the social or cultural fit of the materials and associated technologies. Our curation of approximately 200 studies enables a preliminary screen and highlights several Peruvian materials that could be applied towards heavy metal attenuation. Those materials include two seashell-based mixed media, a mixture of fungi, three new plant species (Peruvian cactus, Peruvian prickly pear, and rose stems), lignin rich compounds such as sawdust from Eucalyptus, corn and rice husk, and food wastes derived from potato, avocado, and green beans. Further studies should explore the social and economic feasibility of these materials. In addition, the site-specific nature of remediation projects is enhanced by the involvement of local communities who are impacted by affected waters and live or work in these areas. In this context, project success and sustainability rely on stakeholder engagement and participation [281].

The synthesis and tabulation provided here can serve as an initial screening tool to triage materials and provide a hierarchy to inform future investigations. Comprehensive adsorption capacity values (mass adsorbate per mass adsorbent) were generally lacking, which limits extrapolation to treatment scenarios. Hence, systematic and standardized experiments (e.g., equilibrium isotherm experiments) should be conducted for promising materials to allow for comparison between materials and the extrapolation of the findings to real-world treatment scenarios.

Commonly used treatment technologies such as chemical precipitation are expensive and require specialized infrastructure and skilled operators for reliable treatment. This paper contributes to a growing body of work that demonstrates that metal-contaminated waters can be treated using inexpensive organic materials. Our focus on southern Peru highlights evidence from local studies and increases the available developing world’s state-of-the-art list (based on earlier reviews and independent studies from the English literature) by 6%. Hence, this represents a valuable contribution to our current knowledge on this important branch of water quality remediation, which could be used in combination with naturally-inspired passive treatment technologies such as wetlands and sulfate reducing bioreactors [276,277] that require less maintenance and upkeep demands. Our synthesis can support further and more detailed studies on how heavy metals have been (and are being) removed from impaired waters using locally available and inexpensive materials and provides a framework for application to other countries in South America and beyond.

Author Contributions: Conceptualization, P.G.-C., V.G., G.M., J.Z., J.T., F.A.; methodology, P.G.-C., J.O.S.; validation, J.V., S.A., G.V., A.M., N.M.S., C.B., J.O.S.; writing—original draft preparation, P.G.-C., V.G., G.M., J.Z., J.T., F.A.; writing—review and editing, J.V., S.A., G.V., A.M., N.M.S., C.B., J.O.S.; project administration, V.G., J.O.S.; funding acquisition, V.G., J.O.S. All authors have read and agreed to the published version of the manuscript.

Funding: Funding for this project was provided by the Center for Mining Sustainability, a joint venture between the Universidad Nacional San Agustin (Arequipa, Peru) and Colorado School of Mines (USA).

Acknowledgments: The authors thank the valuable contributions from Autoridad Nacional del Agua (Peru), and the Center for Sustainable Mining. We dedicate this work to Felix Cuadros (R.I.P.) for his mentorship of both students and faculty in the broader research theme of metal-impaired environments.

Conflicts of Interest: The authors declare no conflict of interest.
Appendix A

Table A1. Removal of ubiquitous metals with limited toxicity in the developing world, in mg/g or (% removal) (Peruvian studies in black color).

| Absorbant                  | Al (III) | Fe (II) | Source                      |
|----------------------------|----------|---------|-----------------------------|
| **Bacteria and Fungi**     |          |         |                             |
| Bacteria, *Bacillus licheniformis* | (52)     | [69]    |                             |
| Bacteria, *Escherichia coli*  | 1 (100)  | [72]    |                             |
| **Plant-Derived**          |          |         |                             |
| Bagasse, sugar cane (*Saccharum officinarum*) | (94)     | [167]   |                             |
| Husk, maize (*Zea mays L.*) | 0.5      | [282]   |                             |
| Peels, avocado (*Persea americana*) | (100)   | [124]   |                             |
| Peels, orange (*Citrus senensis*) | (98)      | [137]   |                             |
| Shells, cocoa (*Theobroma cacao*) | 0.1      | [155]   |                             |
| **Mixed Media**            |          |         |                             |
| Bacteria. *Streptococcus thermophilus* and *Lactobacillus delbrueckii*, var. *Bulgaricus* | (100) | [111] |                             |
| Fungi. *Alternaria sp.*, *Aspergillus sp.*, *Pseudocamarosporium sp.*, and *Penicillium sp.* | (96) | [112] |                             |

References

1. Dura, G.; Kambourova, V.; Simeonova, F. Management of Intentional and Accidental Water Pollution; Springer Science and Business Media LLC: Dordrecht, The Netherlands, 2006.
2. Domenech, X.; Peral, J. Química Ambiental de Sistemas Terrestres; Editorial Reverté: Barcelona, Spain, 2006; p. 256.
3. Eróstegui, C. Contaminación por metales pesados. Rev. Cient. Cienc. Mód. 2009, 12, 45–46.
4. Baird, C.; Cann, M. Química Ambiental; Editorial Reverté: Barcelona, Spain, 2014; p. 622.
5. Tepanosyan, G.; Sahakyan, L.; Belyaeva, O.; Asmaryan, S.; Saghatelyan, A. Continuous impact of mining activities on soil heavy metals levels and human health. Sci. Total. Environ. 2018, 639, 900–909. [CrossRef] [PubMed]
6. Baccar, R.; Bouzid, J.; Feki, M.; Montiel, A. Preparation of activated carbon from Tunisian olive-waste cakes and its application for adsorption of heavy metal ions. J. Hazard. Mater. 2009, 162, 1522–1529. [CrossRef] [PubMed]
7. Caviedes, D.I.; Muñoz, R.A.; Perdomo, A.; Rodríguez, D.; Sandoval, I.J. Tratamientos para la Remoción de Metales Pesadamente Presentes en Aguas Residuales Industriales. Una Revisión. Ingeniería y Región 2015, 13, 73. (In Spanish) [CrossRef]
8. Wang, Y.H.; Lin, S.H.; Juang, R.S. Removal of heavy metal ions from aqueous solutions using various low-cost adsorbents. J. Hazard. Mater. 2003, 102, 291–302. [CrossRef]
9. Unlù, N.; Ersoz, M. Adsorption characteristics of heavy metal ions onto a low cost biopolymeric sorbent from aqueous solutions. J. Hazard. Mater. 2006, 136, 272–280. [CrossRef]
10. Hua, M.; Zhang, S.; Pan, B.; Zhang, W.; Lü, L.; Zhang, Q. Heavy metal removal from water/wastewater by nanosized metal oxides: A review. J. Hazard. Mater. 2012, 211–212, 317–331. [CrossRef]
11. Wang, W.; Chen, M.; Guo, L.; Wang, W.-X. Size partitioning and mixing behavior of trace metals and dissolved organic matter in a South China estuary. Sci. Total. Environ. 2017, 603, 434–444. [CrossRef]
12. Kumar, A.; Rao, N.; Kaul, S. Alkali-treated straw and insoluble straw xanthate as low cost adsorbents for heavy metal removal—Preparation, characterization and application. Bioresour. Technol. 2000, 71, 133–142. [CrossRef]
13. Saravanan, R.; Ravikumar, L. Cellulose bearing Schiff base and carboxylic acid chelating groups: A low cost and green adsorbent for heavy metal ion removal from aqueous solution. Water Sci. Technol. 2016, 74, 1780–1792. [CrossRef]
14. Renu; Agarwal, M.; Singh, K. Heavy metal removal from wastewater using various adsorbents: A review. *J. Water Reuse Desalin.* 2016, 7, 387–419. [CrossRef]

15. Pathak, P.D.; Mandavgane, S.A.; Kulkarni, B.D. Fruit peel waste as a novel low-cost bio adsorbent. *Rev. Chem. Eng.* 2015, 31, 361–381. [CrossRef]

16. Akpomie, K.G.; Dawodu, F.A. Treatment of an automobile effluent from heavy metals contamination by an eco-friendly montmorillonite. *J. Adv. Res.* 2015, 6, 1003–1013. [CrossRef] [PubMed]

17. Markovic, R.; Stevanovic, J.; Stevanovic, Z.; Bugarin, M.; Nedeljkovic, D.; Grujic, A.; Stajić-Trošić, J. Using the Low-Cost Waste Materials for Heavy Metals Removal from the Mine Wastewater. *Mater. Trans.* 2011, 52, 1849–1852. [CrossRef]

18. El-Naggar, I.M.; Ahmed, S.A.; Shehata, N.; Sheneshen, E.S.; Fathy, M.; Shehata, A. A novel approach for the removal of lead (II) ion from wastewater using Kaolinite/Smectite natural composite adsorbent. *Appl. Water Sci.* 2019, 9, 1–13. [CrossRef]

19. Al-Qahtani, K.M. Water purification using different plant fruit cresses for the removal of heavy metals. *J. Taibah Univ. Sci.* 2016, 10, 700–708. [CrossRef]

20. El-Said, G.F.; El-Sadaawy, M.M.; Aly-Eldeen, M.A. Adsorption isotherms and kinetic studies for the defluoridation from aqueous solution using eco-friendly raw marine green algae, Ulva lactuca. *Environ. Monit. Asses.* 2018, 190, 1–15. [CrossRef]

21. Al Dwairi, R.; Omar, W.; Al-Harahsheh, A. Kinetic modelling for heavy metal adsorption using Jordanian low cost natural zeolite (fixed bed column study). *J. Water Reuse Desalin.* 2015, 5, 231–238. [CrossRef]

22. Witek-Krowiak, A.; Szafran, R.G.; Modelski, S. Biosorption of heavy metals from aqueous solutions onto peanut shell as a low-cost biosorbent. *Desalination* 2011, 265, 126–134. [CrossRef]

23. Chuah, T.; Jumasiah, A.; Azni, I.; Katayon, S.; Choong, S.T. Rice husk as a potentially low-cost biosorbent for heavy metal and dye removal: An overview. *Desalination* 2005, 175, 305–316. [CrossRef]

24. Bailey, S.E.; Olin, T.J.; Bricka, R.; Adrian, D. A review of potentially low-cost sorbents for heavy metals. *Water Res.* 1999, 33, 2469–2479. [CrossRef]

25. Fu, F.; Wang, Q. Removal of heavy metal ions from wastewaters: A review. *J. Environ. Manag.* 2011, 92, 407–418. [CrossRef] [PubMed]

26. Kanamarlapudi, S.L.R.K.; Chintalpudi, V.K.; Muddada, S. Application of Biosorption for Removal of Heavy Metals from Wastewater. In *Biosorption;* IntechOpen: London, UK, 2018; pp. 69–116. [CrossRef]

27. Joseph, L.; Jun, B.-M.; Flora, J.R.; Park, C.M.; Yoon, Y. Removal of heavy metals from water sources in the developing world using low-cost materials: A review. *Chemosphere* 2019, 229, 142–159. [CrossRef]

28. MINAM. *Aprende a Prevenir los Efectos del Mercurio. Manual de Salud y Ambiente*; MINAM: Lima, Peru, 2016; p. 32.

29. Aquino, P. *Calidad del Agua en el Perú: Retos y Aportes Para Una Gestión Sostenible en Aguas Residuales;* Derecho Ambiente y Recursos Naturales (DAR): Lima, Peru, 2017; p. 136.

30. MINAM. *Evaluación de la Contaminación Ambiental Causada por la Pequeña Minería y Minería Artesanal en la Zona Urbana del Distrito de Chía;* MINAM: Arequipa, Peru, 2015; p. 81.

31. ANA. *Informe de Identificación de Fuentes Contaminantes en la Cuenca del Río Táumo (Alto Táumo);* Autoridad Nacional del Agua: Cerro Colorado District, Peru, 2013; p. 205.

32. Martínez, W.; Marchena, A.; Otero, J.; Cervantes, J. Tectonomagmatismo y fertilidad de los depósitos porfíricos del Jurásico al Neógeno, sur de Perú. Instituto Geológico, Minero y Metalárgico—INGEMMET; XIX Congreso Peruano de Geología: Lima, Perú, 2018; p. 5.

33. MINSA. *Strategia Sanitaria Nacional de Vigilancia y Control de Riesgos de Contaminación con Metales Pesados u Otras Sustancias Químicas;* MINAM: Lima, Peru, 2013; p. 17.

34. Cooke, C.A.; Balcom, P.H.; Biester, H.; Wolfe, A.P. Over three millennia of mercury pollution in the Peruvian Andes. *Proc. Natl. Acad. Sci. USA* 2009, 106, 8830–8834. [CrossRef] [PubMed]

35. Villena, J. Calidad de agua y desarrollo sostenible. *Rev. Peruana Med. Exp. Salud Pub.* 2008, 35, 304–308. [CrossRef]

36. Peto, M.V. *Aluminium and Iron in Humans: Bioaccumulation, Pathology, and Removal. Rejuvenation Res.* 2010, 13, 589–598. [CrossRef] [PubMed]

37. Romera, E.; González, E.; Ballester, A.; Blázquez, M.L.; Muñoz, J.A. Biosorption of Cd, Ni, and Zn with Mixtures of Different Types of Algae. *Environ. Eng. Sci.* 2008, 25, 999–1008. [CrossRef]
38. Hashim, M.A.; Chu, K. Biosorption of cadmium by brown, green, and red seaweeds. *Chem. Eng. J.* 2004, 97, 249–255. [CrossRef]

39. Ferrarò, G.; Toranzo, R.M.; Castiglioni, D.M.; Lima, E.; Mansilla, M.V.; Fellenz, N.A.; Zysler, R.D.; Pasquevich, D.M.; Bagnato, C. Zinc removal by *Chlorella* sp. biomass and harvesting with low cost magnetic particles. *Algal Res.* 2018, 33, 266–276. [CrossRef]

40. Aksu, Z. Equilibrium and kinetic modelling of cadmium(II) biosorption by *C. vulgaris* in a batch system: Effect of temperature. *Sep. Purif. Technol.* 2001, 21, 285–294. [CrossRef]

41. Davis, T.A.; Volesky, B.; Mucci, A. A review of the biochemistry of heavy metal biosorption by brown algae. *Bioresour. Technol.* 2011, 102, 5297–5304. [CrossRef] [PubMed]

42. Lee, Y.C.; Chang, S.P. The biosorption of heavy metals from aqueous solution by Spirogyra and Cladophora filamentous macroalgae. *Bioresour. Technol.* 2004, 95, 1377–1386. [CrossRef] [PubMed]

43. Suni, K.; Guzmán, D. Bioadsorción de Cu (II), de Aguas Residuales Mineras, con Cochayuyo (*Chondracanthus Chamissoi*); Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2019; p. 120.

44. Al Homaidan, A.A.; Al-Houri, H.J.; Al-Hazzani, A.A.; Elgaaly, G.; Moubayed, N.M. Biosorption of copper from aqueous solution on Spirulina platensis. *Bioresour. Technol.* 2010, 101, 6021–6030. [CrossRef]

45. Murphy, V.; Hughes, H.; McLoughlin, P. Comparative study of chromium biosorption by red, green and brown seaweed biomass. *Chemosphere* 2008, 70, 1128–1134. [CrossRef]

46. Bermúdez, Y.G.; Rico, I.L.R.; Bermúdez, O.G.; Guibal, E. Nickel biosorption using Gracilaria caudata and Sargassum muticum. *Chem. Eng. J.* 2011, 166, 122–131. [CrossRef]

47. Davis, T.A.; Voelenky, B.; Mucci, A. A review of the biochemistry of heavy metal biosorption by brown algae. *Water Res.* 2003, 37, 4311–4330. [CrossRef]

48. Gupta, V.K.; Rastogi, A.; Nayak, A. Biosorption of nickel onto treated alga (*Oedogonium hatei*): Application of isotherm and kinetic models. *J. Colloid Interface Sci.* 2010, 342, 533–539. [CrossRef]

49. Lodeiro, P.; Cordero, B.; Barriada, J.L.; Herrero, R.; Vicente, M.E.S.D. Biosorption of cadmium by biomass of brown marine macroalgae. *Chemosphere* 2014, 4311–4330. [CrossRef]

50. Volesky, B. Removal of heavy metals by biosorption. In *Harnessing Biotechnology for the 21st Century*; Ladisch, M.R., Bose, A., Eds.; American Chemical Society: Washington, DC, USA, 1992; pp. 301–316.

51. Amézquita, E. Remoción de Cadmio Bivalente (Cd²⁺) Mediante Bioadsorción en un Sistema de Flujo Continuo Empacado con Biomasa Muerta e Inmovilizada de Scenedesmus Obliquus (turpin) a Escala de Laboratorio; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 90.

52. Lee, Y.C.; Chang, S.P. The biosorption of heavy metals from aqueous solution by Spirogyra and Cladophora filamentous macroalgae. *Bioresour. Technol.* 2004, 95, 1377–1386. [CrossRef] [PubMed]

53. Celekli, A.; Yavuzatmaca, M.; Bozkurt, H. An eco-friendly process: Predictive modelling of copper adsorption from aqueous solution on Spirulina platensis. *J. Hazard. Mater.* 2010, 173, 123–129. [CrossRef] [PubMed]

54. Al Homaidan, A.A.; Al-Houri, H.J.; Al-Hazzani, A.A.; Elgaaly, G.; Moubayed, N.M. Biosorption of copper from aqueous solution on Spirulina platensis. *Bioresour. Technol.* 2010, 101, 6021–6030. [CrossRef] [PubMed]

55. Celekli, A.; Yavuzatmaca, M.; Bozkurt, H. An eco-friendly process: Predictive modelling of copper adsorption from aqueous solution on Spirulina platensis. *J. Hazard. Mater.* 2010, 173, 123–129. [CrossRef] [PubMed]

56. Villanueva, J. Determinación de la Bioremoción de Plomo (Pb+2) Mediante Hongos y Microalgas Nativas Aisladas de Efluentes Industriales Empacadas en un Sistema en Serie de Agitación Continua; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2015; p. 78. (In Spanish)
62. Valdez, A.; Herrera, R. Evaluación de Factores para la Elaboración de Briquetas a Partir de Conchas de Mejillón (Mytilidae), Carbón Vegetal y Arcilla Bentonita y su Aplicación en la Remoción de Hg\textsuperscript{2+}; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 110. (In Spanish)

63. Salazar, D.I.; Rodríguez, L.A. Desarrollo y Evaluación de un Material Adsorbente a Partir de Residuos Orgánicos para la Adsorción de Cu\textsuperscript{2+} en Soluciones Sintéticas. Bachelor’s Thesis, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru, 2017; p. 133. (In Spanish).

64. Hasan, S.H.; Srivastava, P. Batch and continuous biosorption of Cu\textsuperscript{2+} by immobilized biomass of Arthrobacter sp. J. Environ. Manag. 2009, 80, 3313–3321. [CrossRef]

65. Joo, J.-H.; Hassan, S.H.; Oh, S.-E. Comparative study of biosorption of Zn\textsuperscript{2+} by Pseudomonas aeruginosa and Bacillus cereus. Int. Biodeterior. Biodegrad. 2010, 64, 734–741. [CrossRef]

66. Vullo, D.L.; Ceretti, H.M.; Daniel, M.A.; Ramírez, J.; Zalts, A. Cadmium, zinc and copper biosorption mediated by Pseudomonas veronii 2E. Bioresour. Technol. 2008, 99, 5574–5581. [CrossRef]

67. Srinath, T.; Verma, T.; Ramteke, P.; Garg, S. Chromium (VI) biosorption and bioaccumulation by chromate resistant bacteria. Chemosphere 2002, 48, 427–435. [CrossRef]

68. Vijayaraghavan, K.; Yun, Y.S. Bacterial biosorbents and biosorption. Biotechnol. Adv. 2008, 26, 266–291. [CrossRef] [PubMed]

69. Samarth, D.P.; Chandekar, C.J.; Bhadekar, R. Biosorption of heavy metals from aqueous solution using Bacillus licheniformis. Int. J. Pure Appl. Sci. Tech. 2012, 10, 12–19.

70. Çolak, F.; Atar, N.; Yazıcıoğlu, D.; Olgun, A. Biosorption of lead from aqueous solutions by Bacillus strains possessing heavy-metal resistance. Chem. Eng. J. 2011, 173, 422–428. [CrossRef]

71. Oztiyork, A. Removal of nickel from aqueous solution by the bacterium Bacillus thuringiensis. J. Hazard. Mater. 2007, 147, 518–523. [CrossRef] [PubMed]

72. Quintelas, C.; Rocha, Z.; Silva, B.; Fonseca, B.; Figueiredo, H.; Tavares, T. Biosorptive performance of an Escherichia coli biofilm supported on zeolite NaY for the removal of Cr(VI), Cd(II), Fe(III) and Ni(II). Chem. Eng. J. 2009, 152, 110–115. [CrossRef]

73. Del Carpio, C. Estudio de la Biosorption de Pb (II) y Cd (II) Usando Como Biomasa a Escherichia coli Aislada de las Aguas Contaminadas del Río Huatanay de la Ciudad del Cusco; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2017; p. 164.

74. Ozdemir, G. Biosorption of chromium(VI), cadmium(II) and copper(II) by Pantoea sp. TEM 18. Chem. Eng. J. 2004, 102, 249–253. [CrossRef]

75. Yu, C.L.; Lu, Z.P.; Ge, F.Z.; Zhao, E.L. Biosorption of Cadmium onto Pseudomonas fluorescens: Application of Isotherm and Kinetic Models. Adv. Mater. Res. 2010, 171, 49–52. [CrossRef]

76. Green-Ruiz, C.R.; Rodríguez-Tirado, V.; Egomez-Gil, B. Cadmium and zinc removal from aqueous solutions by Bacillus jeotgali: pH, salinity and temperature effects. Bioresour. Technol. 2008, 99, 3864–3870. [CrossRef]

77. Uslu, G.; Tanyol, M. Equilibrium and thermodynamic parameters of single and binary mixture biosorption of lead (II) and copper (II) ions onto Pseudomonas putida: Effect of temperature. J. Hazard. Mater. 2006, 135, 87–93. [CrossRef]

78. Abd-Alla, M.H.; Morsy, F.M.; El-Enany, A.-W.E.; Ohyama, T. Isolation and characterization of a heavy-metal-resistant isolate of Rhizobium leguminosarum bv. viciae potentially applicable for biosorption of Cd\textsuperscript{2+} and Co\textsuperscript{2+}. Int. Biodeterior. Biodegrad. 2012, 67, 48–55. [CrossRef]

79. Subbaiah, M.V.; Vijaya, Y.; Reddy, A.S.; Yuvaraja, G.; Krishnaiyah, A. Equilibrium, kinetic and thermodynamic studies on the biosorption of Cu(II) onto Trametes versicolor biomass. Desalination 2011, 276, 310–316. [CrossRef]

80. Vimala, R.; Das, N. Biosorption of cadmium (II) and lead (II) from aqueous solutions using mushrooms: A comparative study. J. Hazard. Mater. 2009, 168, 376–382. [CrossRef] [PubMed]

81. Iram, S.; Shabbir, R.; Zafar, H.; Javaid, M. Biosorption and Bioaccumulation of Copper and Lead by Heavy Metal-Resistant Fungal Isolates. Arab. J. Sci. Eng. 2015, 40, 1867–1873. [CrossRef]

82. Dursun, A.Y.; Uslu, G.; Tepe, O.; Cuci, Y.; Ekiz, H. A comparative investigation on the bioaccumulation of heavy metal ions by growing Rhizopus arrhizus and Aspergillus niger. Biochem. Eng. J. 2003, 15, 87–92. [CrossRef]

83. Dursun, A.; Uslu, G.; Cuci, Y.; Aksu, Z. Bioaccumulation of copper(II), lead(II) and chromium(VI) by growing Aspergillus niger. Proc. Biochem. 2003, 38, 1647–1651. [CrossRef]
84. Gulati, R.; Saxena, R.; Gupta, R. Fermentation waste of Aspergillus terreus: A potential copper biosorbent. World J. Microbiol. Biotechnol. 2002, 18, 397–401. [CrossRef]

85. Li, J.; Zheng, B.; He, Y.; Zhou, Y.; Chen, X.; Ruan, S.; Yang, Y.; Dai, C.; Tang, L. Antimony contamination, consequences and removal techniques: A review. Ecotoxicol. Environ. Saf. 2018, 156, 125–134. [CrossRef]

86. Tunali, S.; Akar, S.T. Zn(II) biosorption properties of Botrytis cinerea biomass. J. Hazard. Mater. 2006, 131, 137–145. [CrossRef]

87. Arica, M.Y.; Bayramoğlu, G. Cr(VI) biosorption from aqueous solutions using free and immobilized biomass of Lentinus sajor-caju: Preparation and kinetic characterization. Colloids Surf. A Physicochem. Eng. Asp. 2005, 253, 203–211. [CrossRef]

88. Yan, G.; Viraraghavan, T. Heavy-metal removal from aqueous solution by fungus Mucor rouxii. Water Res. 2003, 37, 4486–4496. [CrossRef]

89. Say, R.; Yılmaz, N.; Denizli, A. Biosorption of Cadmium, Lead, Mercury, and Arsenic Ions by the Fungus Penicillium purpurogenum. Sep. Sci. Technol. 2003, 38, 2039–2053. [CrossRef]

90. Fan, T.; Liu, Y.; Feng, B.; Zeng, G.; Yang, C.; Zhou, M.; Zhou, H.; Tan, Z.; Wang, X. Biosorption of cadmium (II), zinc (II) and lead (II) by Penicillium simplicissimum: Isotherms, kinetics and thermodynamics. J. Hazard. Mater. 2008, 160, 655–661. [CrossRef]

91. Quina, B. Tratamiento de Efluentes de Curtiembres Utilizando Hongos Nativos Filamentosos y Carbón Activado Para la Remoción de Cromo Total; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2019; p. 84.

92. Say, R.; Yılmaz, N.; Denizli, A. Removal of Heavy Metal Ions Using the Fungus Penicillium Canescens. Adsorpt. Sci. Technol. 2003, 21, 643–650. [CrossRef]

93. Holan, Z.R.; Volesky, B. Accumulation of cadmium, lead, and nickel by fungal and wood biosorbents. Appl. Biochem. Biotechnol. 1995, 53, 133–146. [CrossRef]

94. Zapana, S. Biorremediación de Efluentes de Curtiembres Mediante Hongos Aislados del Parque Industrial de Río seco (PIRS)–Arequipa, en Condiciones de Biorreactor tipo Airlift; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 95.

95. Galun, M.; Galun, E.; Siegel, B.Z.; Keller, P.; Lehr, H.; Siegel, S.M. Removal of metal ions from aqueous solutions by Penicillium biomass: Kinetic and uptake parameters. Water Air Soil Pollut. 1987, 33, 359–371. [CrossRef]

96. Ceribasi, I.H.; Yetis, U. Biosorption of Ni(ii) and Pb(ii) by Phanerochaete chrysosporium from a binary metal system–Kinetics. Water SA 2004, 27, 15–20. [CrossRef]

97. Gabriel, J.; Kofronová, O.; Rychlovský, P.; Krenzelok, M. Accumulation and effect of cadmium in the wood-rotting basidiomycete Daedaeula quercina. Bull. Environ. Contam. Toxic. 1996, 57, 383–390. [CrossRef]

98. De Silóniz, M.-I.; Balsalobre, L.; Alba, C.; Valderrama, M.-J.; Peinado, J.M. Feasibility of copper uptake by the yeast Pichia guilliermondii isolated from sewage sludge. Res. Microbiol. 2002, 153, 173–180. [CrossRef]

99. Arbanah, M.; Miradatul, M.; Ku, K. Utilization of Pleurotus ostreatus in the removal of Cr (VI) from chemical laboratory waste. Int. Refreed. J. Eng. Sci. 2013, 2, 29–39.

100. Yahaya, Y.A.; Don, M.M.; Bhatia, S. Biosorption of copper (II) onto immobilized cells of Pycnoporus sanguineus from aqueous solution: Equilibrium and kinetic studies. J. Hazard. Mater. 2009, 161, 189–195. [CrossRef]

101. Arbanah, M.; Miradatul, M.; Ku, K. Utilization of Pleurotus ostreatus in the removal of Cr (VI) from chemical laboratory waste. Int. Refreed. J. Eng. Sci. 2013, 2, 29–39.

102. Yahaya, Y.A.; Don, M.M.; Bhatia, S. Biosorption of copper (II) onto immobilized cells of Pycnoporus sanguineus from aqueous solution: Equilibrium and kinetic studies. J. Hazard. Mater. 2009, 161, 189–195. [CrossRef]

103. Ozer, A.; Ozer, D. Comparative study of the biosorption of Pb(II), Ni(II) and Cr(VI) ions onto S. cerevisiae: Determination of biosorption heats. J. Hazard. Mater. 2003, 100, 219–229. [CrossRef]

104. Huang, C.-P.; Huang, C.-P.; Morehart, A.L. The removal of Cu(II) from dilute aqueous solutions by Saccharomyces cerevisiae. Water Res. 1990, 24, 433–439. [CrossRef]

105. Göksungur, Y. Biosorption of cadmium and lead ions by ethanol treated waste baker’s yeast biomass. Bioreour. Technol. 2005, 96, 103–109. [CrossRef] [PubMed]

106. Padmavathy, V.; Vasudevan, P.; Dhingra, S.C. Biosorption of nickel(II) ions on Baker’s yeast. Process. Biochem. 2003, 38, 1389–1395. [CrossRef]

107. Padmavathy, V. Biosorption of nickel(II) ions by baker’s yeast: Kinetic, thermodynamic and desorption studies. Bioreour. Technol. 2008, 99, 3100–3109. [CrossRef]
108. Fernández, J.; Guzmán, K. Bioadsorción de Cromo (VI) con Saccharomyces Cerevisiae Inmovilizada, Como Residuo de la Elaboración de la Cerveza, Para su Aplicación en Biorremediación de Aguas Contaminadas de la Industria del Curtidor; Universidad Católica de Santa María: Arequipa, Peru, 2019; p. 124.

109. Ksheminska, H.; Fedorovych, D.; Babyak, L.; Yanovych, D.; Kaszycki, P.; Koloczek, H. Chromium(III) and (VI) tolerance and bioaccumulation in yeast: A survey of cellular chromium content in selected strains of representative genera. Process. Biochem. 2005, 40, 1565–1572. [CrossRef]

110. Subbaiah, M.V.; Yun, Y.S. Biosorption of Nickel(II) from aqueous solution by the fungal mat of Trametes versicolor (rainbow) biomass: Equilibrium, kinetics, and thermodynamic studies. Biotechnol. Bioprocess Eng. 2013, 18, 280–288. [CrossRef]

111. Sofu, A.; Sayilgan, E.; Guney, G. Experimental design for removal of Fe (II) and Zn (II) ions by different lactic acid bacteria biomasses. Int. J. Environ. Res. 2015, 9, 93–100.

112. Aymara, C. Bioremoción de Metales eóxidos Mediante Cepas Fúngicas Nativas Aisladas de Efluentes Industriales en un Sistema de Biorreactores en Serie de Agitación Continua; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 113.

113. Ramirez, A. Evaluación del Proceso de Biosorción de la Irrigación del Chenopodium Quinoa (quinua) Para la Remoción de Cromo (VI); Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 73.

114. Elangovan, R.; Philip, L.; Chandraraj, K. Biosorption of chromium species by aquatic weeds: Kinetics and mechanism studies. J. Hazard. Mater. 2008, 152, 100–112. [CrossRef] [PubMed]

115. Malkoc, E. Ni(II) removal from aqueous solutions using cone biomass of Thuja orientalis. J. Hazard. Mater. 2006, 137, 899–908. [CrossRef]

116. Lee, S.-H.; Yang, J.-W. Removal of Copper in Aqueous Solution by Apple Wastes. Sep. Sci. Technol. 1997, 32, 1371–1387. [CrossRef]

117. Erdogan, S.; Önal, Y.; Akmil-Ba¸sar, C.; Bilmez-Erdemo˘glu, S.; Sarıcı-Özdemir, Ç.; Köseoglu, E.; Içduygu, G. Acid bacteria biomasses. Int. J. Environ. Res. 2012, 55, 899–908. [CrossRef]

118. Ahmad, A.; Ghazi, Z.A.; Saeed, M.; Ilyas, M.; Ahmad, R.; Khattak, A.M.; Iqbal, A. A comparative study of the removal of Cr(vi) from synthetic solution using natural biosorbents. New J. Chem. 2017, 41, 10799–10807. [CrossRef]

119. Flores, A.; Silva, F. Caracterización Fisicoquímica en el Tratamiento del Agua con la Utilización de la “Cumulopuntia unguispina” para la Remoción de Metales Pesados de la Irrigación San Camilo del Distrito de la Joya Arequipa; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2019; p. 79.

120. Dakiky, M.; Khamis, M.; Manassra, A.; Mer’Eb, M. Selective adsorption of chromium(VI) in industrial wastewater using low-cost abundantly available adsorbents. Adv. Environ. Res. 2002, 6, 533–540. [CrossRef]

121. Singha, B.; Das, S.K. Biosorption of Cr(VI) ions from aqueous solutions: Kinetics, equilibrium, thermodynamics and desorption studies. Colloids Surfaces B Biointerfaces 2011, 84, 221–232. [CrossRef] [PubMed]

122. Singha, B.; Das, S.K. Adsorptive removal of Cu(II) from aqueous solution and industrial effluent using natural agricultural wastes. Colloids Surfaces B Biointerfaces 2013, 107, 97–106. [CrossRef]

123. Weng, C.-H.; Wu, Y.-C. Potential Low-Cost Biosorbent for Copper Removal: Pineapple Leaf Powder. J. Environ. Eng. 2012, 138, 286–292. [CrossRef]

124. Escobedo, E. Biosorción de Aluminio y Manganeso Total, Presentes en Soluciones Acuosas, con Cascara de Palta (Persica Americana mill) Tratada con Formaldehído; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 93.

125. Quispe, J.; Quispe, S. Bioadsorción con Una Bioresina Intercambiadora de Cationes a Partir de la Masa Paradisíaca (Cáscara de Plátano), Para Eliminar Metales Pesados en Aguas Contaminadas Provenientes de la Planta Concentradora de Minas Bataas; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2019; p. 109.

126. Thirimavalavan, M.; Lai, Y.-L.; Lin, L.-C.; Lee, J.-F. Cellulose-Based Native and Surface Modified Fruit Peels for the Adsorption of Heavy Metal Ions from Aqueous Solution: Langmuir Adsorption Isotherms. J. Chem. Eng. Data 2010, 55, 1186–1192. [CrossRef]

127. Annadurai, G.; Juang, R.; Lee, D. Adsorption of heavy metals from water using banana and orange peels. Water Sci. Technol. 2003, 47, 185–190. [CrossRef]

128. DeMessie, B.; Sahle-Demessie, E.; Sorial, G.A. Cleaning Water Contaminated with Heavy Metal Ions Using Pyrolyzed Biochar Adsorbents. Sep. Sci. Technol. 2015, 50, 2448–2457. [CrossRef]
129. Memon, J.R.; Memon, S.Q.; Bhuanger, M.I.; Khuhawar, M.Y. Banana peel: A green and economical sorbent for Cr(III) removal. Pak. J. Anal. Environ. Chem. 2016, 9, 20–25.

130. Horsfall, M.J.; Spiff, A.I.; Abia, A. Studies on the influence of mercaptocetic acid (MAA) modification of cassava (Manihot scelenta cranz) waste biomass on the adsorption of Cu2+ and Cd2+ from aqueous solution. Bull. Korean Chem. Soc. 2004, 25, 969–976.

131. Kurniawan, A.; Kosasih, A.N.; Febrianto, J.; Ju, Y.H.; Sunarso, J.; Indraswati, N.; Ismadji, S. Evaluation of cassava peel waste as lowcost biosorbent for Ni-sorption: Equilibrium, kinetics, thermodynamics and mechanism. Chem. Eng. J. 2011, 172, 158–166. [CrossRef]

132. Linares, J. Remoción de Iones Plomo (II) de Aguas Sintéticas Mediante el Biosorbente Obtendido de la Cáscara de Castaña (Bertholletia excelsa); Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 101.

133. Saha, R.; Mukherjee, K.; Saha, I.; Ghosh, A.; Ghosh, S.K.; Saha, B. Removal of hexavalent chromium from water by adsorption on mosambi (Citrus limetta) peel. Res. Chem. Intermed. 2012, 39, 2245–2257. [CrossRef]

134. Cabrera, D. Óxido de Zinco (ZnO) como Adsorbente. Estudio de la Determinación de la Actividad Floculante en Aguas Provenientes del Río Chili Conteniendo As, Pb y Cr Tratados con Pectina Obttenidos a Partir de la Cáscara de Naranja, Limón y Mandarina; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 92.

135. Pandey, R.; Ansari, N.G.; Prasad, R.L.; Murthy, R.C. Pb(II) removal from aqueous solution by Cucumis sativus (cucumber) peel: Kinetic, equilibrium & thermodynamic study. Am. J. Environ. Prot. 2014, 2, 51–58.

136. Torab-Mostaedi, M.; Asadollahzadeh, M.; Hemmati, A.; Khosravi, A. Equilibrium, kinetic, and thermodynamic studies for biosorption of cadmium and nickel on grapefruit peel. J. Tai. Ins. Chem. Eng. 2013, 44, 295–302. [CrossRef]

137. Salas, P.; Sarcco, L. Eliminación de Plomo (II) y Fierro (II), por Bioadsorción con Cáscara de Naranja (Citrus Sinensis) en Residuos Líquidos Procedentes del Laboratorio Químico del sur del Perú; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2017; p. 109.

138. Aguilar, M.; Flores, C. Evaluación de la Cáscara de Naranja (Citrus Sinensis) Como Material Absorbente Natural de Ion Metálico Cu(II); Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 113.

139. Feng, N.; Guo, X.; Liang, S.; Zhu, Y.; Liu, J. Biosorption of heavy metals from aqueous solutions by chemically modified orange peel. J. Hazard. Mater. 2011, 185, 49–54. [CrossRef]

140. Abdelhafez, A.A.; Li, J. Removal of Pb(II) from aqueous solution by using biochars derived from sugar cane bagasse and orange peel. J. Taiwan Inst. Chem. Eng. 2016, 51, 367–375. [CrossRef]

141. Lugo, V.L.; Hernández-López, S.; Barrera-Díaz, C.; Ureña-Nuñez, F.; Bilyeu, B. A comparative study of natural, formaldehyde-treated and copolymer-grafted orange peel for Pb(II) adsorption under batch and continuous mode. J. Hazard. Mater. 2009, 161, 1255–1264. [CrossRef] [PubMed]

142. Ghosh, A.; Sinha, K.; Das Saha, P. Central composite design optimization and artificial neural network modeling of copper removal by chemically modified orange peel. Desalin. Water Treat. 2013, 51, 7791–7799. [CrossRef]

143. Feng, N.; Guo, X.; Liang, S. Adsorption study of copper (II) by chemically modified orange peel. J. Hazard. Mater. 2009, 164, 1286–1292. [CrossRef]

144. Bhatnagar, A.; Minocha, A. Biosorption optimization of nickel removal from water using Punica granatum peel waste. Colloids Surfaces B Biointerfaces 2010, 76, 544–548. [CrossRef]

145. Weber, T.W.; Chakravorti, R.K. Pore and solid diffusion models for fixed-bed adsorbers. AIChE J. 1974, 20, 228–238. [CrossRef]

146. Miranda, L. Biosorción de Plomo (II), Presente en Soluciones Acuosas, con Cáscara de Tuna (Opuntia Ficus—Indica); Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2012; p. 106.

147. Al-Ghouti, M.A.; Li, J.; Salamh, Y.; Al-Laqath, N.; Walker, G.; Ahmad, M.N. Adsorption mechanisms of removing heavy metals and dyes from aqueous solution using date pits solid adsorbent. J. Hazard. Mater. 2010, 176, 510–520. [CrossRef]

148. Córdova, A.; Medina, M. Bioremovición con Semilla de Papaña Arequipeña (Vasconcellea pubescens) Para Cromo total en Efluentes de Curtiembres, Arequipa; Universidad Católica de Santa Maria: Arequipa, Peru, 2019; p. 264.

149. Boonnumuyvitaya, V.; Chaiya, C.; Thanthapanichakoon, W.; Jarudilokkhol, S. Removal of heavy metals by adsorbent prepared from pyrolyzed coffee residues and clay. Sep. Purif. Technol. 2004, 35, 11–22. [CrossRef]

150. Cabrera, D. Evaluación de la Capacidad de Biosorción de Plomo (II) Empleando Biomasa Vegetal Inerte (Tallo de Rosas) Como Adsorbente; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 171.
151. Ordoñez, J.L.; Moreno, R.A. Estudio del Aprovechamiento de Residuos Orgánicos de Cultivo de Flores (Tallos de Rosa) Como Biosorbente de Cadmio para el Tratamiento de Aguas Residuales; Universidad Politécnica Salesiana: Cuenca, Ecuador, 2013; p. 100.

152. Villaescusa, I.; Fiol, N.; Martínez, M.; Miralles, N.; Pojch, J.; Serarols, J. Removal of copper and nickel ions from aqueous solutions by grape stalk wastes. *Water Res.* **2004**, *38*, 992–1002. [CrossRef]

153. Kumar, P.S.; Ramalingam, S.; Kirupha, S.D.; Murugesan, A.; Vidhyadevi, T.; Sivanesan, S. Adsorption behavior of nickel(II) onto cashew nut shell: Equilibrium, thermodynamics, kinetics, mechanism and process design. *Chem. Eng. J.* **2011**, *167*, 122–131. [CrossRef]

154. Basso, M.C.; Cerrella, E.G.; Cukierman, A.L. Lignocellulosic Materials as Potential Biosorbents of Trace Toxic Metals from Wastewater. *Environ. Monit. Assess.* **2003**, *90*, 255–263. [CrossRef]

155. Meunier, N.; Laroulandie, J.; Blais, J.; Tyagi, R. Cocoa shells for heavy metal removal from acidic solutions. *Bioresour. Technol.* **2003**, *90*, 28, 247–255. [CrossRef]

156. Pino, G.H.; DeMesquita, L.M.S.; Torem, M.L.; Pinto, G.A.S. Biosorption of Heavy Metals by Powder of Green Coconut Shell. *Sep. Sci. Technol.* **2006**, *41*, 3141–3153. [CrossRef]

157. Senthilkumar, P.; Ramalingam, S.; Sathyaselvakala, V.; Kirupha, S.D.; Sivanesan, S. Removal of copper(II) ions from aqueous solution by adsorption using cashew nut shell. *Desalination* **2011**, *266*, 63–71. [CrossRef]

158. Shukla, S.; Pai, R.S. Adsorption of Cu(II), Ni(II) and Zn(II) on dye loaded groundnut shells and sawdust. *Sep. Purif. Technol.* **2004**, *43*, 1–8. [CrossRef]

159. Landaburu-Aguiirre, J.; García, V.; Pongrácz, E.; Keiski, R.L. The removal of zinc from synthetic wastewaters by micellar-enhanced ultrafiltration: Statistical design of experiments. *Desalination* **2009**, *240*, 262–269. [CrossRef]

160. Basci, N.; Kocadagistan, E.; Kocadagistan, B. Biosorption of copper (II) from aqueous solutions by wheat shell. *Desalination* **2004**, *164*, 135–140. [CrossRef]

161. Martins, R.J.; Pardo, R.; Boaventura, R.A. Cadmium(II) and zinc(II) adsorption by the aquatic moss *Fontinalis antipyretica*: Effect of temperature, pH and water hardness. *Water Res.* **2004**, *38*, 693–699. [CrossRef]

162. Orhan, Y.; Büyükgüngör, H. The Removal of Heavy Metals by Using Agricultural Wastes. *Water Sci. Technol.* **1993**, *28*, 247–255. [CrossRef]

163. Basci, N.; Kocadagistan, E.; Kocadagistan, B. Biosorption of copper (II) from aqueous solutions by wheat shell. *Desalination* **2004**, *164*, 135–140. [CrossRef]

164. Demirbas, E.; Dizge, N.; Sulak, M.; Kobya, M. Adsorption kinetics and equilibrium of copper from aqueous solutions using hazelnut shell activated carbon. *Chem. Eng. J.* **2009**, *148*, 480–487. [CrossRef]

165. Basso, M.C.; Cerrella, E.G.; Cukierman, A.L. Lignocellulosic Materials as Potential Biosorbents of Trace Toxic Metals from Wastewater. *Ind. Eng. Chem. Res.* **2002**, *41*, 3580–3585. [CrossRef]

166. Ordoñez, J.L.; Moreno, R.A. Estudio del Aprovechamiento de Residuos Orgánicos de Cultivo de Flores (Tallos de Rosa) Como Biosorbente de Cadmio para el Tratamiento de Aguas Residuales; Universidad Politécnica Salesiana: Cuenca, Ecuador, 2013; p. 100.

167. Kumar, P.S.; Ramalingam, S.; Kirupha, S.D.; Murugesan, A.; Vidhyadevi, T.; Sivanesan, S. Adsorption behavior of nickel(II) onto cashew nut shell: Equilibrium, thermodynamics, kinetics, mechanism and process design. *Chem. Eng. J.* **2011**, *167*, 122–131. [CrossRef]

168. Senthilkumar, P.; Ramalingam, S.; Sathyaselvakala, V.; Kirupha, S.D.; Sivanesan, S. Removal of copper(II) ions from aqueous solution by adsorption using cashew nut shell. *Desalination* **2011**, *266*, 63–71. [CrossRef]

169. Villaescusa, I.; Fiol, N.; Martínez, M.; Miralles, N.; Pojch, J.; Serarols, J. Removal of copper and nickel onto bagasse fly ash. *Chem. Eng. J.* **2009**, *148*, 480–487. [CrossRef]

170. Alom, I.; Martín-Lara, M.Á.; Rodríguez, I.; Blázquez, G.; Calero, M. Removal of nickel (II) ions from aqueous solutions by biosorption on sugarcane bagasse. *J. Taiwan Inst. Chem. Eng.* **2012**, *43*, 275–281. [CrossRef]

171. Moubarik, A.; Grimi, N. Valorization of olive stone and sugar cane bagasse by-products as biosorbents for the removal of cadmium from aqueous solution. *Food Res. Int.* **2015**, *73*, 169–175. [CrossRef]

172. Moubarik, A.; Grimi, N. Valorization of olive stone and sugar cane bagasse by-products as biosorbents for the removal of cadmium from aqueous solution. *Food Res. Int.* **2015**, *73*, 169–175. [CrossRef]

173. Srivastava, S.; Agrawal, S.; Mondal, M.K. Biosorption isotherms and kinetics on removal of Cr(VI) using native and chemically modified Lagerstroemia speciosa bark. *Ecol. Eng.* **2015**, *85*, 56–66. [CrossRef]
174. Reddy, D.H.K.; Ramana, D.; Seshaih, K.; Reddy, A. Biosorption of Ni(II) from aqueous phase by Moringa oleifera bark, a low cost biosorbent. Desalination 2011, 268, 150–157. [CrossRef]

175. Villaescusa, I.; Martinez, M.; Miralles, N. Heavy metal uptake from aqueous solution by cork and yohimbe bark wastes. J. Chem. Tech. Biotechnol. 2000, 75, 1–5. [CrossRef]

176. Argun, M.E.; Dursun, Ş.; Karatas, M. Removal of Cd(II), Pb(II), Cu(II) and Ni(II) from water using modified pine bark. Desalination 2009, 249, 519–527. [CrossRef]

177. Naiya, T.K.; Bhattacharya, A.; Das, S. Adsorption of Pb(II) by sawdust and neem bark from aqueous solutions. Environ. Prog. 2008, 27, 313–328. [CrossRef]

178. Montes-Atenas, G.M.; Schroeder, S.L.M. Sustainable natural adsorbents for heavy metal removal from wastewater: Lead sorption on pine bark (Pinus radiataD.Don). Surf. Interface Anal. 2015, 47, 996–1000. [CrossRef]

179. Al-Asheh, S.; Duvnjak, Z. Binary Metal Sorption by Pine Bark: Study of Equilibria and Mechanisms. Sep. Sci. Technol. 1998, 33, 1303–1329. [CrossRef]

180. Randall, J.M.; Huatala, E.; Waiss, A.C., Jr.; Tschernitz, J.L. Modified barks as scavengers for heavy metal ions. Forest Prod. J. 1976, 27, 51–56.

181. Kumar, P.; Dara, S.S. Utilization of agricultural wastes for decontaminating industrial/domestic wastewaters from toxic metals. Agric. Wastes 1982, 4, 213–223. [CrossRef]

182. Henderson, R.W.; Andrews, D.S.; Lightsey, G.R.; Poonawala, N.A. Reduction of mercury, copper, nickel, cadmium, and zinc levels in solution by competitive adsorption onto peanut hulls, and raw and aged bark. Bull. Environ. Contam. Toxicol. 1977, 17, 355–359. [CrossRef]

183. Deshicar, A.; Bokade, S.; Dara, S. Modified hardwickia binata bark for adsorption of mercury (II) from water. Indian J. Environ. Health 1980, 22, 196–202.

184. Randall, J.M. Variation in effectiveness of barks as scavengers for heavy metal ions. Forest Prod. J. 1977, 26, 46–50.

185. Poonawala, N.A.; Lightsey, G.R.; Hines, A.L.; Henderson, R.W. Removal of heavy metals from wastewater and sludge by adsorption onto solid wastes. J. Water Resour. 1990, 24, 1011–1016. [CrossRef]

186. Mamani, R.; Acosta-Rodriguez, I. Adsorption of cadmium(II) from aqueous solution by natural and oxidized corn cob. Sep. Purif. Technol. 2005, 45, 41–49. [CrossRef]

187. Leyva-Ramos, R.; Bernal-Jacome, L.; Acosta-Rodriguez, I. Adsorption of cadmium(II) from aqueous solution on natural and oxidized corn cob. Sep. Purif. Technol. 2005, 45, 41–49. [CrossRef]

188. Salazar, B.; Zea, G. Estudio del Proceso de Biosorción del Endocarpio de Aceituna (Olea Europea) para la Remoción de Plomo (II) y Cadmio (II) de Soluciones Acuosas; Universidad Católica de Santa María: Arequipa, Peru, 2015; p. 71.

189. Argun, M.E.; Dursun, Ş.; Karatas, M. Removal of Cd(II), Pb(II), Cu(II) and Ni(II) from water using modified pine bark. Desalination 2009, 249, 519–527. [CrossRef]

190. Balseca, H.; Arequipa, Peru, 2015; p. 106.

191. Rosas, Y. Caracterización y Remoción de Cromo (III) de Aguas Residuales de Curtiembres del Parque Industrial de Río Seco Utilizando Hueso de Olivo (Olea Europea) Procesado Como Biosorbente; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2017; p. 71.

192. Sun, Z.; Liu, Y.; Huang, Y.; Tan, X.; Zeng, G.; Hu, X.; Yang, Z. Fast adsorption of Cd2+ and Pb2+ by EGTA dianhydride (EGTAD) modified ramie fiber. J. Colloid Interface Sci. 2014, 434, 152–158. [CrossRef]

193. Zhu, C.-S.; Wang, L.-P.; Chen, W.-B. Removal of Cu(II) from aqueous solution by agricultural by-product: Peanut hull. J. Hazard. Mater. 2009, 168, 739–746. [CrossRef]

194. Johnson, P.D.; Watson, M.A.; Brown, J.; Jefcoat, L.A. Peanut hull pellets as a single use sorbent for the capture of Cu(II) from wastewater. Waste Manag. 2002, 22, 471–480. [CrossRef]

195. Hasar, H. Adsorption of nickel(II) from aqueous solution onto activated carbon prepared from almond husk. J. Hazard. Mater. 2003, 97, 49–57. [CrossRef]
197. Sewwandi, B.G.N.; Vithanage, M.; Wijesekara, S.; Mowjood, M.; Hamamoto, S.; Kawamoto, K. Adsorption of Cd(II) and Pb(II) onto Humic Acid–Treated Coconut (Cocos nucifera) Husk. J. Hazardous Toxic Radioact. Waste 2014, 18, 04014001. [CrossRef]

198. Li, Q.; Zhai, J.; Zhang, W.; Wang, M.; Zhou, J. Kinetic studies of adsorption of Pb(II), Cr(III) and Cu(II) from aqueous solution by sawdust and modified peanut husk. J. Hazard. Mater. 2007, 141, 163–167. [CrossRef]

199. Krishnani, K.K.; Meng, X.; Christodoulatos, C.; Boddu, V.M. Biosorption mechanism of nine different heavy metals onto biomatrix from rice husk. J. Hazard. Mater. 2008, 153, 1222–1234. [CrossRef] [PubMed]

200. Bansal, M.; Garg, U.; Singh, D.; Garg, V. Removal of Cr(VI) from aqueous solutions using pre-consumer processing agricultural waste: A case study of rice husk. J. Hazard. Mater. 2009, 162, 312–320. [CrossRef] [PubMed]

201. Abdel-Ghani, N.T.; Hefny, M.; El-Chaghaby, G.A.F. Removal of lead from aqueous solution using low cost abundantly available adsorbents. Int. J. Environ. Sci. Technol. 2007, 4, 67–73. [CrossRef]

202. Bhattacharyya, K.G.; Sharma, A. Adsorption of Pb(II) from aqueous solution by Azadirachta indica (Neem) leaf powder. J. Hazard. Mater. 2004, 113, 97–109. [CrossRef]

203. Guo, X.; Zhang, S.; Shu, X.-Q. Adsorption of metal ions on lignin. J. Hazard. Mater. 2008, 151, 134–142. [CrossRef] [PubMed]

204. Wu, Y.; Zhang, S.; Guo, X.; Huang, H. Adsorption of chromium(III) on lignin. Bioresour. Technol. 2008, 99, 7709–7715. [CrossRef]

205. Rao, R.A.K.; Khan, M.A. Biosorption of bivalent metal ions from aqueous solution by an agricultural waste: Kinetics, thermodynamics and environmental effects. Colloids Surfaces A Physicochem. Eng. Asp. 2009, 332, 121–128. [CrossRef]

206. Singha, A.S.; Guleria, A. Utility of chemically modified agricultural waste okra biomass for removal of toxic heavy metal ions from aqueous solution. Eng. Agric. Environ. Food 2015, 8, 52–60. [CrossRef]

207. Friedman, M.; Waiss, A.C. Mercury uptake by selected agricultural products and by-products. Environ. Sci. Technol. 1972, 6, 457–458. [CrossRef]

208. Aksu, Z.; İsoğlu, İ.A. Removal of copper(II) ions from aqueous solution by biosorption onto agricultural waste sugar beet pulp. Process. Biochem. 2005, 40, 3031–3044. [CrossRef]

209. Cañazaca, C.; Ccama, W. Biosíntesis de Nanopartículas de Hierro Cero Valente (NZVI) Usando Hojas de Eucalipto (Eucalyptus sp.) para la Remoción de Cromo Hexavalente; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2017; p. 159.

210. Yu, B.; Zhang, Y.; Shukla, A.; Shukla, S.S.; Dorris, K.L. The removal of heavy metals from aqueous solutions by sawdust adsorption—Removal of lead and comparison of its adsorption with copper. J. Hazard. Mater. 2001, 84, 83–94. [CrossRef]

211. Cárdenas, S.; Ortega, J. Modelamiento y Simulación de Una Columna de Adsorción de Lecho Fijo Para la Remoción de Cr (VI) de Soluciones Acuosas Utilizando Aserrín Como Adsorbente; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2015; p. 209.

212. Suemitsu, R.; Osako, M.; Tagiri, N. The use of dyestuff-treated sawdusts for removal of heavy metals from waste water. Sci. Eng. Rev. Doshisha. Univ. 1986, 27, 41–48.

213. Bozic, D.; Gorgievski, M.; Stankovic, V.; Strbacb, N.; Serbula, S.; Petrovic, N. Adsorption of heavy metal ions by beech sawdust e kinetics, mechanism and equilibrium of the process. Ecol. Eng. 2013, 58, 202–206. [CrossRef]

214. Rafatullah, M.; Sulaiman, O.; Hashim, R.; Ahmad, A. Adsorption of copper (II), chromium (III), nickel (II) and lead (II) ions from aqueous solutions by meranti sawdust. J. Hazard. Mater. 2009, 170, 969–977. [CrossRef] [PubMed]

215. Saeed, A.; Akhter, M.W.; Iqbal, M. Removal and recovery of heavy metals from aqueous solution using papaya wood as a new biosorbent. Sep. Purif. Technol. 2005, 45, 25–31. [CrossRef]

216. Shukla, S.S.; Yu, L.J.; Dorris, K.L.; Shukla, A. Removal of nickel from aqueous solutions by sawdust. J. Hazard. Mater. 2005, 121, 243–246. [CrossRef]

217. Peñilván, E.; Altun, T. Parlayıcı, Şerife Utilization of barley straws as biosorbents for Cu2+ and Pb2+ ions. J. Hazard. Mater. 2009, 164, 982–986. [CrossRef]

218. Thevannan, A.; Mungroo, R.; Niu, C.H. Biosorption of nickel with barley straw. Bioresour. Technol. 2010, 101, 1776–1780. [CrossRef]
219. Dang, V.; Doan, H.; Dang-Vu, T.; Lohi, A. Equilibrium and kinetics of biosorption of cadmium(II) and copper(II) ions by wheat straw. *Bioresour. Technol.* 2009, 100, 211–219. [CrossRef]

220. Ho, Y.S.; Chuang, Y.C.; Huang, H. Equilibrium sorption isotherm for metal ions on tree fern. *Process. Biochem.* 2002, 37, 1421–1430. [CrossRef]

221. Abdolali, A.; Ngo, H.H.; Guo, W.; Lu, S.; Chen, S.-S.; Nguyen, N.C.; Zhang, X.; Wang, J.; Wu, Y. A breakthrough biosorbent in removing heavy metals: Equilibrium, kinetic, thermodynamic and mechanism analyses in a lab-scale study. *Sci. Total. Environ.* 2016, 542, 603–611. [CrossRef]

222. Herrera, A.; Sosa, S. Evaluación y Comparación de la Biosorción de Cr (VI) Usando Cascaras de Cuatro Variedades de Papa (Solanum Tuberosum) Universidad Católica de Santa María: Arequipa, Peru, 2018; p. 99.

223. Pacheco, J. Evaluación del Proceso de Biosorción de Cr (VI) Usando Residuos Agroindustriales de la Región Arequipa (Cascarilla de Arroz y Chita de Maíz) Universidad Católica de Santa María: Arequipa, Peru, 2019; p. 102.

224. Zevallos, C. Obtención de Carbón Activado a Partir de Residuos Orgánicos de Gypsophila Elegans (Ilusión) del Distrito de Cayma y su Evaluación como Adsorbente de plomo (II) en Solución Acusa; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 87.

225. Hossain, M.; Ngo, H.H.; Guo, W.; Nguyen, T.V.; Vigneswaran, S. Performance of cabbage and cauliflower wastes for heavy metals removal. *Desalin. Water Treat.* 2013, 52, 844–860. [CrossRef]

226. Güzel, F.; Yakut, H.; Topal, G. Determination of kinetic and equilibrium parameters of the batch adsorption of Mn(II), Co(II), Ni(II) and Cu(II) from aqueous solution by black carrot (*Daucus carota* L.) residues. *J. Hazard. Mater.* 2008, 153, 1275–1287. [CrossRef] [PubMed]

227. Nasernejad, B.; Zadeh, T.E.; Pour, B.B.; Bygi, M.E.; Zamani, A. Comparison for biosorption modeling of heavy metals (Cr(III), Cu(II), Zn(II)) adsorption from wastewater by carrot residues. *Proc. Biochem.* 2005, 40, 1319–1322. [CrossRef]

228. Johari, K.; Saman, N.; Song, S.T.; Mat, H.; Stuckey, D. Utilization of Coconut Milk Processing Waste as a Low-Cost Mercury Sorbent. *Ind. Eng. Chem. Res.* 2013, 52, 15648–15657. [CrossRef]

229. Ewecharoen, A.; Thiravetyan, P.; Nakbanpote, W. Comparison of nickel adsorption from electroplating rinse water by coir pith and modified coir pith. *Chem. Eng. J.* 2008, 137, 181–188. [CrossRef]

230. Andrade, E. Descontaminación de Pb(II) de Aguas Residuales Mineras, por Adsorción con Estiércol de Vaca (bosta); Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2019; p. 123.

231. Aguaro, J.; Onofre, E. Investigación Para Controlar en las Aguas Residuales Industriales la Contaminación con Cromo, Usando Cascaras de Nuevo Calcinado, en Soluciones Sintéticas y Posterior Aplicación a las Aguas Contaminadas Reales; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2018; p. 110.

232. Salazar, B. Evaluación del Proceso de Biosorción de Pb (II) y Cd (II) en Agua Utilizando el Residuo Agrícola de Phaseolus vulgaris L. (frijol) Universidad Católica de Santa María: Arequipa, Peru, 2017; p. 92.

233. Kyzas, G.Z.; Terzopoulou, Z.; Nikolaidis, V.; Alexopoulou, E.; Bikiaris, D.N. Low-cost hemp biomaterials for heavy metals (Cr(III), Cu(II), Zn(II)) adsorption from wastewater by carrot residues. *J. Molec. Liq.* 2015, 209, 209–218. [CrossRef]

234. Huang, Z.; Zhang, B.; Fang, G. Adsorption Behavior of Cr(VI) from Aqueous Solutions by Microwave Modified Porous Larch Tannin Resin. *BioResources* 2013, 8, 4593–4608. [CrossRef]

235. Saman, N.; Johari, K.; Song, S.T.; Kong, H.; Cheu, S.-C.; Mat, H. High removal efficacy of Hg(II) and MeHg(II) ions from aqueous solution by organoalkoxysilane-grafted lignocellulosic waste biomass. *Chemosphere* 2017, 171, 19–30. [CrossRef]

236. Suryan, S.; Ahluwalia, S. Biosorption of Heavy Metals by Paper Mill Waste from Aqueous Solution. *Int. J. Environ. Sci.* 2012, 2, 1331–1343. [CrossRef]

237. Moussavi, G.; Barikbin, B. Biosorption of chromium(VI) from industrial wastewater onto pistachio hull waste biomass. *Chem. Eng. J.* 2010, 162, 893–900. [CrossRef]

238. Wang, X.; Li, Z.Z.; Sun, C. A comparative study or removal of Cu(II) from aqueous solutions by locally low-cost materials: Marine macroalgae and agricultural by product. *Desalination* 2009, 235, 146–159. [CrossRef]

239. Khormaei, M.; Nasernejad, B.; Edrisi, M.; Eslamzadeh, T. Copper biosorption from aqueous solutions by sour orange residue. *J. Hazard. Mater.* 2007, 149, 269–274. [CrossRef] [PubMed]

240. Marshall, W.; Waltelle, L.; Boles, D.; Johns, M.; Toles, C. Enhanced metal adsorption by soybean hulls modified with citric acid. *Bioresour. Technol.* 1999, 69, 263–268. [CrossRef]

241. Malakahmad, A.; Tan, S.; Yavari, S. Valorization of Wasted Black Tea as a Low-Cost Adsorbent for Nickel and Zinc Removal from Aqueous Solution. *J. Chem.* 2016, 2016, 1–8. [CrossRef]
242. Mohammed, R. Removal of heavy metals from waste water using black tea waste. *Arab. J. Sci. Eng.* 2012, 37, 1505–1520. [CrossRef]

243. Weng, C.-H.; Lin, Y.-T.; Hong, D.-Y.; Sharma, Y.C.; Chen, S.-C.; Tripathi, K.M. Effective removal of copper ions from aqueous solution using base treated black tea waste. *Ecol. Eng.* 2014, 67, 127–133. [CrossRef]

244. Yang, S.; Wu, Y.; Aierken, A.; Zhang, M.; Fang, P.; Fan, Y.; Ming, Z. Mono/competitive adsorption of Arsenic(III) and Nickel(II) using modified green tea waste. *J. Taiwan Inst. Chem. Eng.* 2016, 60, 213–221. [CrossRef]

245. Malkoc, E.; Nuhoglu, Y. Potential of tea factory waste for chromium(VI) removal from aqueous solutions: Thermodynamic and kinetic studies. *Sep. Purif. Technol.* 2007, 54, 291–298. [CrossRef]

246. Malkoc, E.; Nuhoglu, Y. Investigations of nickel(II) removal from aqueous solutions using tea factory waste. *J. Hazard. Mater.* 2005, 127, 120–128. [CrossRef]

247. Nuhoglu, Y.; Malkoc, E. Thermodynamic and kinetic studies for environmentally friendly Ni(II) biosorption using waste pomace of olive oil factory. *Bioresour. Technol.* 2009, 100, 2375–2380. [CrossRef] [PubMed]

248. Villar, L. Gypsophila. In *Flora Iberica, Volume 15: Rubiaceae to Caprifoliaceae*; Consejo Superior de Investigaciones Científicas: Madrid, Spain, 1990; pp. 408–415.

249. Sánchez, M.; Klašnja, M.; Antov, M.G. Study of the biosorption of different heavy metal ions onto Kraft lignin. *Ecol. Eng.* 2011, 37, 2092–2095. [CrossRef]

250. Kirk, P.M.; Cannon, P.F.; Minter, D.W.; Stalpers, J.A. *Dictionary of the Fungi*; CABI Publishing: Wallingford, UK, 2008; 784p.

251. Lee, R.E. *Phycolgy*; Cambridge University Press (CUP): Cambridge, UK, 2018; p. 508.

252. Dance, S.P. *Shells: The Clearest Recognition Guide Available*; DK Publisher: London, UK, 2002; p. 256.

253. Christensen, M.; Frisvad, J.C.; Tuthill, D.E. Penicillium Species Diversity in Soil and Some Taxonomic and Ecological Notes. In *Integration of Modern Taxonomic Methods for Penicillium and Aspergillus Classification*; Harwood Academic: Reading, UK, 2000; pp. 285–298.

254. Kirk, P.M.; Cannon, P.F.; Minter, D.W.; Stalpers, J.A. *Dictionary of the Fungi*; CABI Publishing: Wallingford, UK, 2008; 784p.

255. Coutinho, P.M.; Andersen, M.R.; Kolenoiva, K.; Vankuyk, P.A.; Benoi, I.; Gruben, B.S.; Trejo-Aguilar, B.; Visser, H.; Van Solingen, P.; Pakula, T. Post-genomic insights into the plant polysaccharide degradation potential of Aspergillus nidulans and comparison to Aspergillus niger and Aspergillus oryzae. *Fungal Genet. Biol.* 2009, 46, S161–S169. [CrossRef] [PubMed]

256. Battaglia, E.; Benoi, I.; Gruben, B.; De Vries, R. Plant Cell Wall Derived Sugars as Substrates for Fungi and Industry. In *The Sugar Industry and Cotton Crops*; Jenkins, P.T., Ed.; Nova Science Publishers: New York, NY, USA, 2010; pp. 65–94.

257. Bautista, M.E.; Leyva, S.G.; Villaseñor, H.E.; Huerta, J.; Mariscal, L.A. Hongos Asociados al Grano de Trigo Sembrado en Áreas del Centro de México. *Rev. Mex. Fitopatol.* 2017, 29, 175–177.

258. Paucha, A.; Quipuscoa, V. Catálogo de las cactáceas del departamento de Arequipa, Perú. *Aranolada* 2017, 24, 447–496. [CrossRef]

259. Kiesling, R. Origen, Domesticación y Distribución de Opuntia ficus-indica (Cactaceae). *J. Prof. Assoc. Cactus Derv.* 1999, 3, 50–60.

260. Villar, L. Gypsophila. In *Flora Iberica, Volume 15: Rubiaceae to Caprifoliaceae*; Consejo Superior de Investigaciones Científicas: Madrid, Spain, 1990; pp. 408–415.

261. Berdgeman, J. Public perception towards water recycling in California. *Water Environ. J.* 2004, 18, 150–154. [CrossRef]

262. Zea, J. Obtención del Alginato de Calcio y su Evaluación como Adsorbente para la Remoción de Plomo; Universidad Nacional de San Agustín de Arequipa: Arequipa, Peru, 2008; p. 88.

263. Lavado-Meza, C.; Sun, M.; Bendezú, S. Adsorción de plomo de efluentes industriales usando carbones activados con H3PO4. *Rev. Soc. Quím. Perú* 2010, 76, 165–178.

264. Xia, Y.; Tang, Y.; Shih, K.; Li, B. Enhanced phosphorus availability and heavy metal removal by chlorination during sewage sludge pyrolysis. *J. Hazard. Mater.* 2020, 382, 121110. [CrossRef]

265. Desta, M.B. Batch Sorption Experiments: Langmuir and Freundlich Isotherm Studies for the Adsorption of Textile Metal Ions onto Teff Straw (*Eragrostis tef*) Agricultural Waste. *J. Thermodyn.* 2013, 2013, 1–6. [CrossRef]
266. Taşar, Ş.; Kaya, F.; Özer, A. Biosorption of lead(II) ions from aqueous solution by peanut shells: Equilibrium, thermodynamic and kinetic studies. *J. Environ. Chem. Eng.* 2014, 2, 1018–1026. [CrossRef]
267. Chen, H.; Zhao, J.; Dai, G.; Wu, J.; Yan, H. Adsorption characteristics of Pb(II) from aqueous solution onto a natural biosorbent, fallen Cinnamomum camphora leaves. *Desalination* 2010, 262, 174–182. [CrossRef]
268. Ayawei, N.; Ebelegi, A.N.; Wankasi, D. Modelling and Interpretation of Adsorption Isotherms. *J. Chem.* 2017, 2017, 1–11. [CrossRef]
269. Subramanyam, B.; Das, A. Linearised and non-linearised isotherm models optimization analysis by error functions and statistical means. *J. Environ. Health Sci. Eng.* 2014, 12, 92. [CrossRef]
270. Crittenden, J.C.; Trussell, R.R.; Hand, D.W.; Howe, K.J.; Tchobanoglous, G. *MWH’s Water Treatment: Principles and Design*; John Wiley & Sons: New York, NY, USA, 2012; p. 1901.
271. Lata, S.; Singh, P.K.; Samadder, S.R. Regeneration of adsorbents and recovery of heavy metals: A review. *Int. J. Environ. Sci. Technol.* 2014, 12, 1461–1478. [CrossRef]
272. Sharma, P.; Kaur, H.; Sharma, M.; Sahore, V. A review on applicability of naturally available adsorbents for the removal of hazardous dyes from aqueous waste. *Environ. Monit. Assess.* 2011, 183, 151–195. [CrossRef]
273. Chowdhury, Z. *Activated Carbon Solutions for Improving Water Quality*; American Water Works Association: Denver, CO, USA, 2013; p. 318.
274. Lund, J.W. Eutrophication. *Nat. Cell Biol.* 1967, 214, 557–558. [CrossRef]
275. Day, A.D.; Ludeke, K.L. *Plant Nutrients in Desert Environments*; Springer Science and Business Media LLC: Berlin, Germany, 1993; p. 117.
276. Drennan, D.M.; Almstrand, R.; Ladderud, J.; Lee, I.; Landkamer, L.; Figueroa, L.; Sharp, J.O. Spatial effects of inorganic ligand availability and localized microbial community structure on mitigation of mining influenced water in sulfate-reducing bioreactors. *Water Res.* 2017, 115, 50–59. [CrossRef] [PubMed]
277. Drennan, D.M.; Almstrand, R.; Lee, I.; Landkamer, L.; Figueroa, L.; Sharp, J.O. Organoheterotrophic Bacterial Abundance Associates with Zinc Removal in Lignocellulose-Based Sulfate-Reducing Systems. *Environ. Sci. Technol.* 2015, 50, 378–387. [CrossRef]
278. UNESCO World Water Assessment Program. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2018; p. 139.
279. Dunlap, A. ‘Agro sí, mina NO!’ the Tía Maria copper mine, state terrorism and social war by every means in the Tambo Valley, Peru. *Politi-Geogr.* 2019, 71, 10–25. [CrossRef]
280. Malone, A.; Smith, N.M.; Zeballos, E. Coexistence and conflict between artisanal mining, fishing, and farming in a Peruvian boomtown. *Geoforum* 2020. (Forthcoming).
281. O’Brien, R.M.; Phelan, T.J.; Smith, N.M.; Smits, K. Remediation in developing countries: A review of previously implemented projects and analysis of stakeholder participation efforts. *Crit. Rev. Environ. Sci. Technol.* 2020, 1–22. [CrossRef]
282. Indah, S.; Helard, D.; Sasmita, A. Utilization of maize husk (Zea mays L.) as low-cost adsorbent in removal of iron from aqueous solution. *Water Sci. Technol.* 2016, 73, 2929–2935. [CrossRef] [PubMed]

**Publisher’s Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).