

PRELIMINARY SCREENING AND CHARACTERIZATION OF FOOD WASTE-DERIVED MATERIALS AS POTENTIAL ADSORBENTS AND BIOCHAR PRECURSORS

Daniela ION^{1,2}, Florentina Laura CHIRIAC^{1*}, Ana-Maria LUNTRARU¹, Mihai STEFANESCU¹, Mihai NIȚĂ-LAZĂR^{1,2*}

¹ National Institute for Research and Development for Industrial Ecology—INCD ECOIND, Bucharest, Romania; daniela.ion@ecoind.ro; (D.I.); laura.chiriac@incdecoind.ro; (F.L.C.); ana.luntrar@ecoind.ro (A.M.L.); mihai.stefanescu@incdecoind.ro; (M.S.); mihai.nita@incdecoind.ro; (M.N.L.)

² Faculty of Biotechnical Systems Engineering, National University of Science and Technology POLITEHNICA Bucharest, Romania; daniela.ion@incdecoind.ro ; (D.I.); mihai.nita@incdecoind.ro; (M.N.L.)

* Correspondence: laura.chiriac@incdecoind.ro (F.L.C.); mihai.nita@incdecoind.ro (M.N.);

Received date: June 12th 2026; Accepted date: Aug. 1st 2026; Published date: Sept. 30th 2026

Water pollution caused by pharmaceutical residues is a growing issue. Conventional treatment processes do not remove all of these contaminants. Because of this, low-cost solution materials are being explored. Agri-food waste may be one option. In this study, walnut, avocado, potato, onion, and eggshells were investigated as potential bioadsorbents and biochar precursors. FTIR analysis, particle size analysis, and dissolved organic carbon were used for characterization and to assess their stability in water. The results provide preliminary information on their physicochemical properties and support their selection for future adsorption experiments with pharmaceutical compounds.

Keywords: agri-food waste; bioadsorbents; characterization; FTIT; DOC

© 2026 by the authors. This article is distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Water pollution with pharmaceutical residues has become an increasing problem in recent decades. These compounds are often found in wastewater, surface water, groundwater, sediment, and even drinking water. This means ecosystems and populations may be exposed for long periods to low but persistent concentrations of contaminants [1,2]. Pharmaceutical residues come from several sources. Human and veterinary excretion are among the main ones. Hospital, industrial effluents and improper disposal of expired medicines also contribute [3,2]. In many cases, drugs are not fully removed after use and can reach aquatic systems. Most conventional wastewater treatment plants are not built to completely eliminate pharmaceutical compounds and their metabolites. During treatment or after entering the

environment, some compounds can change through photolysis, hydrolysis, or biodegradation. This may lead to transformation products that remain in the environment and can also be toxic [4]. Some studies report endocrine disruption, feminization, and increasing antibiotic resistance. At the same time, the long-term exposure effects on human health are still not fully understood [5].

The topic becomes more important with the European legislation. The revised Urban Wastewater Treatment Directive (UWWTD, 2024) asks for the implementation of a quaternary stage. It also requires the removal of at least 80% of priority micropollutants, including pharmaceutical residues and other emerging contaminants. Because of this, there is increasing pressure to find treatment methods that are effective, cheaper, and easier to apply. At the same time, agri-food waste is still a problem. Large amounts of biomass from food processing and households are generated every year [6,7]. If not managed properly, this waste can contribute to greenhouse gas emissions and leachate formation in landfills [8,9]. One idea discussed more often in recent studies is to reuse food waste as biosorbents or biochar for water treatment. However, numerous studies are mixed. Results depend on the precursor materials, activation method or testing conditions. In some cases, materials work well, in others, less. There is still no clear agreement on which waste performs best for pharmaceutical removal. Also, many reported materials need chemical activation or show limited potential for regeneration and reuse [10].

The study focused on food waste that is easy to find locally, such as walnut shells, avocados, potatoes, onions, and eggshells. These residues were prepared and characterized as potential precursor materials for future development of bioadsorbents and biochars intended for pharmaceutical removal from water. Many of them contain lignocellulosic compounds and functional groups such as hydroxyl, carboxyl, and phenolic groups, which may contribute to interactions with organic contaminants [11,12]. Still, their actual adsorption performance depends on several physicochemical and operational factors, including porous structure, surface chemistry, pH, temperature, or contact time. The study also considers food residues that are often generated in Romania and usually have low value or are discarded. An integrated physicochemical characterization was performed to compare their properties and identify the materials with the most promising characteristics for subsequent adsorption studies. This approach is consistent with circular economy and green chemistry principles by exploring possible value-added applications for food waste. The present work provides the preliminary information required for the selection of materials and the design of future adsorption, kinetics, equilibrium, and regeneration experiments. Therefore, the objective of this study was to prepare and characterize selected food wastes and evaluate their physicochemical suitability as potential bioadsorbents or precursors for obtaining biochar intended for future pharmaceutical removal applications.

The novelty of this study lies in the comparative screening of five locally available food wastes with markedly different organic and mineral compositions, evaluated under the same preparation and characterization conditions. Their combined assessment by FTIR, particle-size distribution, and DOC release provides an initial basis for identifying material-specific limitations, particularly aqueous stability and secondary organic carbon release, before adsorption experiments are performed.

2. Materials and Methods

2.1 Materials

The peels of onions (*Allium cepa*), potatoes (*Solanum tuberosum*), avocados (*Persea americana*), walnuts (*Juglans*), and eggs (*Gallus gallus domesticus*) were collected gradually from household human activities. The collection period was around 5–6 months. These residues were selected based on their local availability and their distinct compositions: lignocellulosic and lignin-rich walnut shells, polysaccharide-rich potato peels, lipid- and lignocellulose-containing avocado peels, phenolic-rich onion peels, and calcium-carbonate-rich eggshells. This compositional diversity enabled the preliminary comparison of materials with different surface chemistries and potential interaction pathways. The study did not aim to establish their superiority over other agri-food residues. Samples collected at different times were washed and dried separately and subsequently combined according to waste type to obtain one composite sample for each material. Each composite sample was ground and homogenized before analysis. This approach was used to reduce the influence of individual collection events. However, variability related to cultivar, season, storage conditions, and food preparation was not evaluated separately and is acknowledged as a limitation of the study. The biomass was washed with Milli-Q distilled water, then individually dried in a UF 110 (Mettler) oven under the following conditions: onion peels at 60 °C for 24 h, potato peels at 65 °C for 24 h, avocado peels at 60 °C for 24 h, walnut shells at 50 °C for 48 h, and eggshells at 105 °C for 24 h. After drying, the samples were shredded using the ZM 200 rotor mill (Retsch, Germany) and stored in a silica gel desiccator (Merck). For the analysis of dissolved organic carbon (DOC), Potassium Hydrogen Phthalate ($C_8H_5O_4K$, CPAchem), certified according to ISO 17025, was used.

2.2 QA&QC

FTIR measurements were performed in duplicate for each composite sample, while DOC analysis was performed in triplicate. Particle-size distribution was measured once for each composite sample and was therefore interpreted

descriptively. DOC was determined in leachates obtained by contacting the dry biomass with Milli-Q water at a solid-to-liquid ratio of 1:10 for 24 h. A procedural blank and a quality-control standard were analyzed with each sample batch. For DOC analysis, 2.0 g of dry biomass was mixed with 20 mL of Milli-Q water, corresponding to a solid-to-liquid ratio of 1:10. The suspensions were subjected to orbital shaking for 24 h at room temperature. After separation of the solid phase, the leachates were analyzed immediately; therefore, no preservation procedure was required. DOC analysis was performed in triplicate. A procedural blank and a quality-control standard were analyzed with each batch. Results were expressed as mg kg^{-1} dry matter. The relative standard deviation established during the repeatability assessment of the method was 3.2%. DOC results were normalized to the dry biomass mass and expressed as mg kg^{-1} dry matter. No inferential statistical analysis was performed because the replicates represented analytical measurements of one composite sample per material rather than independent biological samples.

2.3 Technical characterization of analytical method equipment

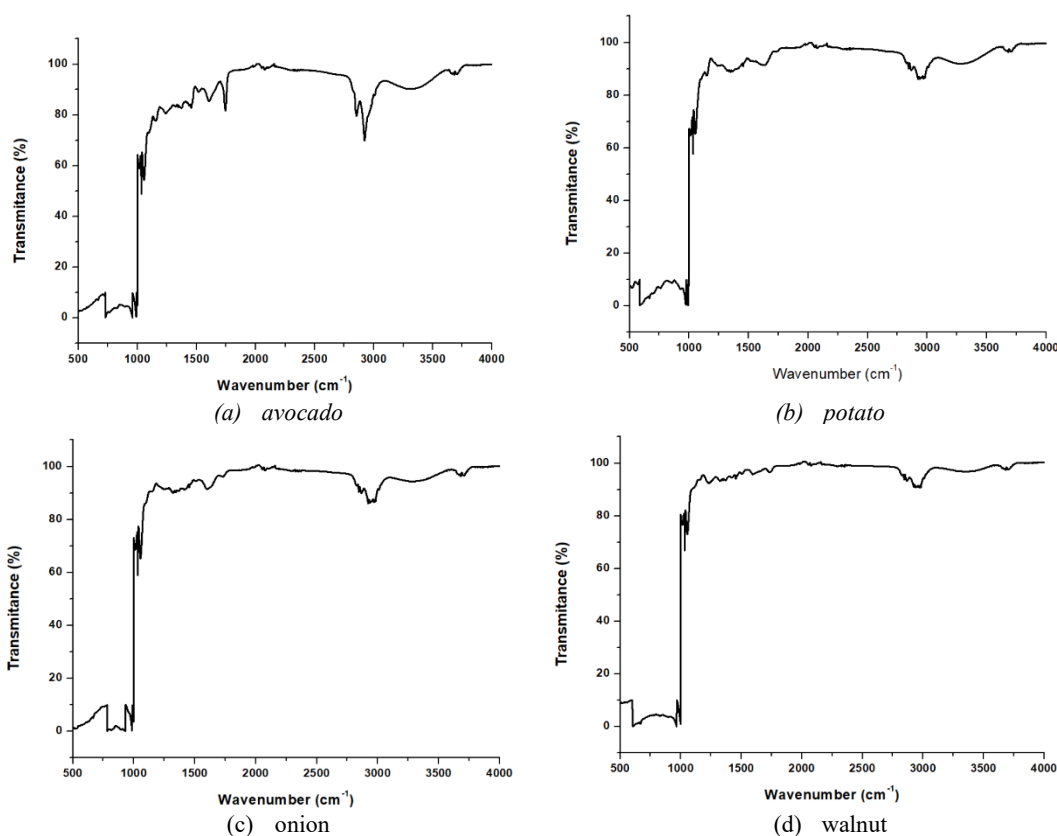
The characterization of the functional clusters of the matrices was performed by Fourier transform infrared spectroscopy (FTIR), using the ATR (Attenuated Total Reflectance) mode for solid samples. The analysis was performed in the $4000\text{--}400\text{ cm}^{-1}$ spectral range, with a resolution of approximately 4 cm^{-1} and 16–64 scans/sample. The method allowed the identification of the main functional groups involved in the adsorption processes, such as --OH , C=O , --COOH , C--O , C--O--C , and C=C aromatic, associated with the lignocellulosic components of biomass (cellulose, hemicellulose and lignin). Particle-size distribution was determined by laser diffraction using a Mastersizer 2000 instrument, software version 5.60, equipped with a Scirocco 2000 dry-dispersion unit (Malvern Instruments Ltd., UK), according to ISO 13320:2009. The dry powdered samples were dispersed in air, with a dispersant refractive index of 1.000. Therefore, no liquid dispersion medium, sonication, or equilibration step was applied. Data were processed using the General Purpose Analysis model with Enhanced Sensitivity, a particle refractive index of 1.538, and an absorption index of 0.1, over a particle-size range of $0.020\text{--}2000\text{ }\mu\text{m}$. Obscuration ranged from 0.13 to 1.02%. Results were expressed as number-based particle-size distributions. One measurement was performed for each composite sample; therefore, the results were interpreted descriptively. Dissolved organic carbon (DOC) was determined using the Shimadzu TOC-L CPH/CPN analyzer, based on high-temperature catalytic oxidation and IR detection of CO_2 , according to the SR EN ISO 20236:2024 standard. Prior to analysis, the samples were filtered through membranes with a pore size of $0.45\text{ }\mu\text{m}$.

3. Results and Discussion

3.1 Analysis (FTIR)

FTIR spectra were recorded in duplicate for each composite sample over the range of 4000–400 cm^{-1} . Spectra were processed by baseline correction, without additional smoothing. One representative spectrum is presented for each material, as duplicate measurements showed comparable spectral profiles.

The identification of $-\text{OH}$, $-\text{COOH}$, $\text{C}=\text{O}$, and $\text{C}-\text{O}$ groups indicates differences in surface chemistry that may influence interactions with organic contaminants; however, FTIR data alone cannot establish adsorption affinity or mechanism [13]. The walnut shell showed bands specific to lignocellulosic materials. The bands around 3400 cm^{-1} and 1600 cm^{-1} indicate the presence of hydroxyl groups and lignin-associated aromatic structures. This suggests a stable, rigid material with physicochemical characteristics that may support interactions with organic molecules [14,15].



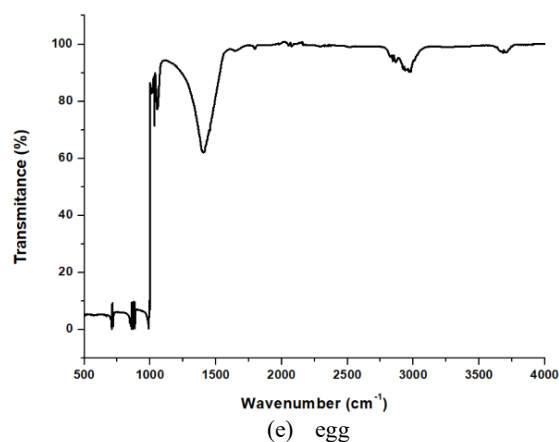


Figure 1. FTIR characterization of raw materials obtained from food scraps. (a) FTIR spectra of avocado peel, (b) FTIR spectra of potato peel, (c) FTIR spectra of onion peel, (d) FTIR spectra of walnut shell, (e) FTIR spectra of eggshell.

In the case of avocado peel, the spectrum indicated a composition rich in oxygenated groups and aliphatic chains. The bands in the $3200\text{--}3600\text{ cm}^{-1}$ area are associated with --OH groups, and those around 2920 and 2850 cm^{-1} indicate the presence of aliphatic C--H bonds. These characteristics may contribute to possible hydrophobic and hydrogen bonding interactions with organic contaminants. However, adsorption affinity and selectivity cannot be established based on FTIR analysis alone [15,16].

The potato peel showed a spectral fingerprint rich in polysaccharides. The intense bands in the $1000\text{--}1200\text{ cm}^{-1}$ area are attributed to the C--O and C--O--C bonds, specific to starch, cellulose, and hemicellulose. The presence of --OH and C=O groups suggests the possibility of hydrogen bonding interactions with polar organic compounds, which must be confirmed through adsorption experiments [17,10]. Onion peels exhibited a greater variety of oxygenated functional groups. The bands around $1700\text{--}1730\text{ cm}^{-1}$ indicate carbonyl groups, and those in the $3200\text{--}3600\text{ cm}^{-1}$ area are associated with hydroxyl groups and phenolic compounds. The presence of pectin and flavonoids, especially quercetin, suggests several possible interaction pathways, including complexation, chelation or ion exchange. Nevertheless, the relevance of these mechanisms cannot be confirmed without adsorption and mechanistic studies [13,18]. The spectrum of eggshells was different from the other materials, being dominated by the inorganic component. The intense bands at approximately 1420 , 875 , and 712 cm^{-1} confirm the presence of calcium carbonate in the form of calcite. Therefore, possible interactions involving ion exchange, pH modification, or surface precipitation may be considered, but their contribution requires experimental verification [14,15]. The main characteristics of the investigated materials are summarized in Table 1.

Table 1. Summary of the main characteristics of the investigated materials.

Material	Peak position (cm ⁻¹)	Relative intensity	Tentative assignment	d(0.5) (μm)	DOC (mg/kg d.w.)
Walnut shell	3340	broad, weak	O–H stretching	5.371	35
	1595	weak	Aromatic C=C vibration associated with lignocellulosic structures		
	1032	strong	C–O and C–O–C stretching in polysaccharides		
Avocado peel	3305	broad, medium	O–H stretching	14.072	362
	2923, 2854	strong/medium	Aliphatic C–H stretching		
	1744	strong	C=O stretching of ester or lipid-associated groups		
Potato peel	3274	broad, medium	O–H stretching	1.427	305
	1629	medium	Bound-water bending and/or carbonyl-related vibration		
	1032	strong	C–O stretching in starch and cellulose		
Onion peel	3274	broad, weak–medium	O–H stretching in hydroxyl and phenolic groups	1.834	333
	1601	medium	Aromatic C=C and/or COO ⁻ vibration		
	1032	strong	C–O and C–O–C stretching in carbohydrates		
Eggshell	1404	very strong	Asymmetric carbonate stretching	10.941	2.4
	858	medium	Out-of-plane carbonate bending		
	708	medium	In-plane carbonate bending		

FTIR analysis showed distinct qualitative spectral profiles among the investigated food wastes. Walnut shell exhibited bands associated with lignocellulosic and aromatic structures, avocado peel showed oxygenated and aliphatic groups, potato peel displayed bands characteristic of polysaccharides, onion peel contained several oxygenated functional groups, and the eggshell spectrum was consistent with a calcium-carbonate-rich composition. These assignments indicate possible differences in surface chemistry but do not establish hydrophobicity, rigidity, reactivity, adsorption affinity, selectivity, or adsorption mechanisms. Such properties require confirmation through complementary characterization and adsorption experiments [15].

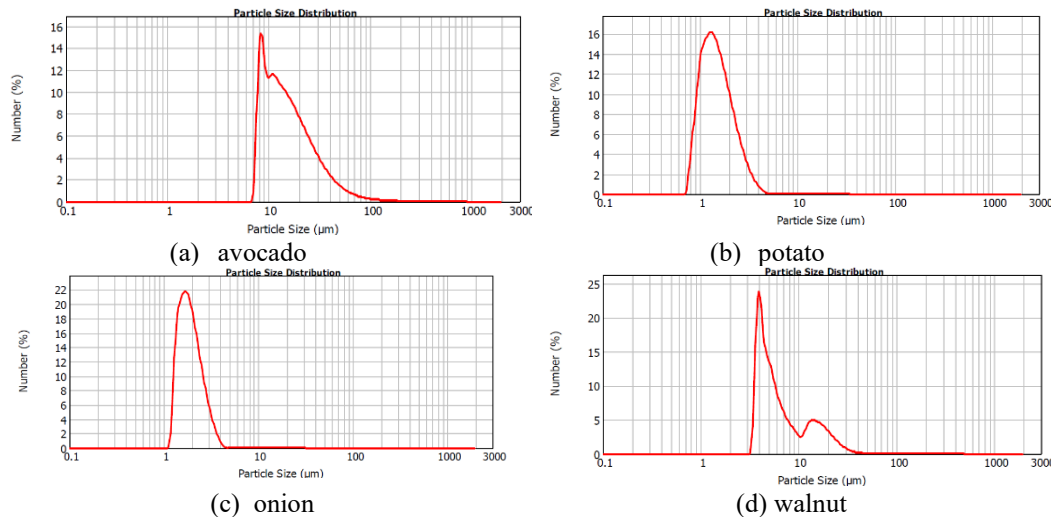
3.2 Particle size distribution of bioadsorbents

Particle size analysis revealed important differences between the materials investigated, both in particle size and uniformity of distribution (Figure 2). These characteristics directly influence the contact surface and the accessibility of the active sites involved in the adsorption. The reported d(0.1), d(0.5), and d(0.9) values

represent number-based particle-size percentiles obtained under dry-dispersion conditions. Because one measurement was performed for each composite sample, the results were interpreted descriptively.

The walnut shell powder showed an uneven distribution with fine and coarse particles. The median particle size, $d(0.5)$, was about $5.37 \mu\text{m}$, and 90% of the particles were less than $17.54 \mu\text{m}$ in size. Most fell within the range of $3\text{--}30 \mu\text{m}$, indicating a heterogeneous and polydisperse material. This type of distribution is typical of ground lignocellulosic biomass, although its influence on adsorption performance requires experimental confirmation [16,11].

The eggshell powder showed a median particle size of approximately $10.94 \mu\text{m}$, while 10% of the particles were smaller than $7.85 \mu\text{m}$ and 90% of the particles remained below $19.28 \mu\text{m}$. The distribution was relatively narrow, with most particles concentrated between approximately 8 and $20 \mu\text{m}$. These results describe only the dimensional characteristics of the material and do not demonstrate increased surface reactivity or adsorption performance [14,19]. The potato peel powder had a relatively uniform distribution and predominantly fine particles. The median $d(0.5)$ value was approximately $1.43 \mu\text{m}$, and the dominant particle range was between 0.96 and $2.46 \mu\text{m}$. The laser-diffraction-estimated specific surface area was $1.35 \text{ m}^2/\text{g}$, the highest among the analyzed materials. This value was calculated by the instrument software from the particle-size distribution, assuming spherical particles and a density of 1.0 g/cm^3 . It is not equivalent to an experimentally measured BET surface area and was not interpreted as evidence of adsorption kinetics or capacity [17,19].



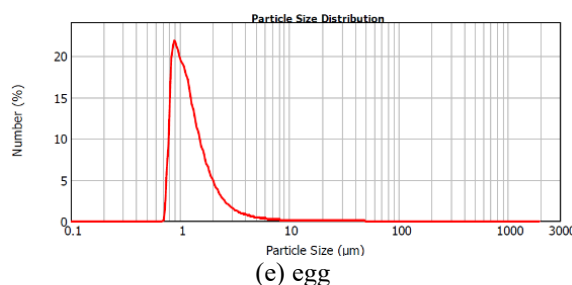


Figure 2. Particle size analysis of raw materials obtained from food waste: (a) Particle size for avocado peel, (b) Particle size for potato peel, (c) Particle size for onion peel, (d) Particle size for walnut shell, (g)) Particle size for eggshell.

In the case of onion peels, the particle size distribution was relatively narrow and uniform. The $d(0.1)$, $d(0.5)$, and $d(0.9)$ values were 1.38, 1.83, and 2.75 μm , respectively. Thus, 50% of the particle number was below 1.83 μm , rather than most particles being below this value. The laser-diffraction-estimated specific surface area was 1.21 m^2/g . These dimensional characteristics may influence the behavior of the material in subsequent adsorption experiments, but no conclusion regarding mass transfer or adsorption efficiency can be drawn from particle-size data alone [19,20]. Avocado peel powder had the largest particle dimensions among the investigated materials. The median value of $d(0.5)$ was approximately 14.07 μm , while the coarse fraction of $d(0.1)$ and $d(0.9)$ were 8.37 and 33.90 μm , respectively. The distribution suggests an even more compact fibrous structure, specific to lignocellulose- and lipid-rich biomass. The laser-diffraction-estimated specific surface area was 0.0328 m^2/g . This calculated value should not be considered equivalent to BET surface area or used as direct evidence of adsorption affinity or capacity [21,22].

The unexpectedly low particle-size values obtained for potato and onion peels may be influenced by the optical parameters, dry-dispersion behavior, and assumptions of the instrument model. Since the optical properties were not determined independently for each biomass and the measurements were not replicated, these values should be considered preliminary and require confirmation using replicate measurements or a complementary microscopic method [23,24].

3.3 Dissolved organic carbon (DOC) analysis

The DOC values highlighted important differences between the analyzed biomasses, suggesting different behaviors in contact with the aqueous environment. The highest values were recorded for avocado peels ($362 \pm 11.6 \text{ mg/kg d.w.}$) and onion peels ($333 \pm 10.6 \text{ mg/kg d.w.}$), indicating an increased release of soluble organic compounds such as sugars, phenolic compounds, and lignocellulosic fragments [18,20]. On the other hand, the eggshell showed the lowest value ($2.4 \pm 0.08 \text{ mg/kg d.w.}$), which confirms the predominantly inorganic character of the

material, rich in calcium carbonate. This result suggests high stability in water and a reduced risk of release of dissolved organic matter. In walnut shell, the DOC value of 35 ± 1.12 mg/kg d.w. indicates a reduced solubility of organic compounds, probably due to the dense lignocellulosic structure, which may be an advantage for adsorption processes [25,15]. The high values observed for avocados and onions may indicate a higher risk of secondary pollution by the release of organic matter into the water. For this reason, these biomasses may require preliminary treatments, such as carbonization or activation, to improve stability and reduce interference in the adsorption process.

3.4 Comparison with the specialized literature

Data from the recent literature show that agri-food waste has been investigated as a potential source for obtaining bioadsorbents for the removal of organic and inorganic pollutants from water. The reported adsorption performance differs considerably depending on the type of biomass, the pretreatment method, target contaminant, and experimental conditions, including initial concentration, adsorbent dose, pH, and contact time. In general, materials used in raw or carbonized state show moderate efficiencies (approx. 40–85%), while chemical activation or surface functionalization can significantly increase the performance of the adsorbent, sometimes up to over 95–100% [11,26,27,14,17]. Removal percentages reported in different studies are not directly comparable and were not used to rank the investigated materials.

Peels of fruits and vegetables, such as banana, citrus, avocado, potato or onion, are among the most investigated materials due to their high availability and lignocellulosic composition. These biomasses have been studied for the removal of antibiotics, anti-inflammatories, and persistent pharmaceutical compounds, including tetracycline, ciprofloxacin, carbamazepine, ibuprofen, or paracetamol [28,25,29,30,15]. Residues such as grape or olive kernels and pomace have also been investigated for antibiotics and anti-inflammatory [31,32,33,10,11]. In the case of biomass from cereals and straw, the reported performance strongly on the carbonization process and experimental conditions [26,28,34,6,9]. These literature data indicate possible applications but do not allow direct quantitative comparison among materials.

Compared to existing studies, the present research focuses on the preliminary characterization of walnut shells, avocados, onions, potatoes, and eggs as potential biosorbents or biochar. The study is limited to FTIR, DOC and particle-size characterization and does not evaluate adsorption capacity, removal efficiency or adsorption mechanisms. The results provide initial information for selecting materials for further physicochemical characterization and subsequent adsorption experiments.

3.5 Future perspectives for adsorption studies

The present study provides only a preliminary screening of selected agri-food wastes. Its main limitations include the absence of adsorption experiments, the use of one composite sample for each material, limited physicochemical characterization, and the lack of information on BET surface area, porosity, pH at the point of zero charge, elemental composition, and thermal stability. Therefore, the current results cannot be used to predict adsorption capacity, selectivity or practical performance.

In the next stage, the materials will undergo additional characterization before being tested for the removal of selected pharmaceutical and personal care products, including carbamazepine, triclosan and triclocarban. Batch adsorption experiments will examine the effects of contact time, initial concentration, pH and adsorbent dose. Removal efficiency, adsorption capacity, kinetic behavior and equilibrium data will then be evaluated.

Biochars will also be prepared from the same raw materials. Their physicochemical properties and adsorption performance will be compared with those of the corresponding untreated biomasses to assess whether thermal treatment improves material stability and contaminant removal.

4. Conclusions

The results highlighted that raw biomass has limitations in the aqueous environment, such as the release of soluble organic compounds and reduced stability, aspects that can affect its suitability for future adsorption applications involving pharmaceutical compounds. The FTIR analysis showed clear structural differences between the materials investigated. The walnut shell showed a lignocellulosic character rich in lignin and aromatic groups, potentially favorable for adsorption; the avocado peel showed a higher content of lipid compounds, and the eggshell a predominantly mineral structure, based on calcium carbonate. The identified functional groupings ($-\text{OH}$, $\text{C}=\text{O}$, $-\text{COOH}$, $\text{C}-\text{O}$) may contribute to interaction with organic pollutants. Particle size analysis and DOC values indicated important differences between biomasses. Avocado and onion peels showed high DOC values, suggesting a possible risk of secondary pollution and the need for pre-treatments. In contrast, walnut and eggshells showed lower DOC values, indicating greater stability in water under the tested conditions. However, no material can be ranked as superior because no predefined multi-criteria framework or adsorption-performance tests were applied. Walnut shell and eggshell may therefore be considered candidates for subsequent characterization and adsorption experiments, together with the other investigated materials. The results support the preliminary screening of agri-food waste-derived materials and their future investigation as potential bioadsorbents for water treatment applications.

Author Contributions

Conceptualization, F.L.C. and M.N.L.; methodology, F.L.C. and M.N.L.; validation, D.I., F.L.C. and M.N.L.; formal analysis, D.I., M.S., A.M.L.; investigation, D.I., M.S. and A.M.L.; writing—original draft preparation, D.I., M.S. and A.M.L., F.L.C. and M.N.L.; writing—review and editing, D.I., M.S. and A.M.L., F.L.C. and M.N.L.; supervision, F.L.C. and M.N.L.; funding acquisition, A.M.L. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

Funding

No funding.

Acknowledgments

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI - UEFISCDI, through the project Center of Excellence in water management, materials, by-products and waste valorisation for circular bioeconomy implementation, proposal number PN-IV-P6-6.1-CoEx-2024-0056, contract 6 CoEx/08.01.2026.

Conflicts of Interest

The authors declare no conflict of interest.

Artificial Intelligence Disclosure

In the preparation of this manuscript, the authors utilized AI to aid in English language editing, as none of the authors are native English speakers Grammarly (version 1.2.291.1949, Grammarly, Inc.). Following this assistance, the authors thoroughly reviewed and edited the content to ensure accuracy and integrity and take full responsibility for the final version. The authors take full responsibility for the manuscript.

Publisher's Disclaimer

The statements, opinions, and data presented in this publication are solely those of the author(s) and contributor(s) and do not necessarily reflect the views of the publisher, editor(s), or affiliated institutions. The publisher and editor(s) disclaim responsibility for any errors, omissions, or consequences arising from the use of the information, methods, instructions, or products described in the publication.

REFERENCES

- [1] Nguyen, M.K.; Lin, C.; Bui, X.T.; Rakib, M.R.J.; Nguyen, H.L.; Truong, Q.M.; Idris, A.M. Occurrence and fate of pharmaceutical pollutants in wastewater: Insights on ecotoxicity, health risk, and state-of-the-art removal, *Chemosphere* **2024**, *354*, 141678, <https://doi.org/10.1016/j.chemosphere.2024.141678>.
- [2] Estrada-Almeida, A.G.; Castrejón-Godínez, M.L.; Mussali-Galante, P.; Tovar-Sánchez, E.; Rodríguez, A. Pharmaceutical pollutants: Ecotoxicological impacts and the use of agro-industrial waste for their removal from aquatic environments, *J. Xenobiot.* **2024**, *14*, 1465–1518, <https://doi.org/10.3390/jox14040082>.
- [3] Yadav, S.; Asthana, A.; Singh, A.K. Adsorption of cationic dyes, drugs and metal from aqueous solutions using a polymer composite of magnetic/ β -cyclodextrin/activated charcoal /Na alginate:

- Isotherm, kinetics and regeneration studies, *J. Hazard. Mater.* **2021**, *409*, 124840, <https://doi.org/10.1016/j.jhazmat.2020.124840>.
- [4] Vinayagam, V.; Murugan, S.; Kumaresan, R.; Narayanan, M.; Sillanpää, M.; N Vo, D.V.; Kushwaha, O.S.; Jenis, P.; Potdar, P.; Gadiya, S. Sustainable adsorbents for the removal of pharmaceuticals from wastewater: A review, *Chemosphere* **2022**, *300*, 134597, <https://doi.org/10.1016/j.chemosphere.2022.134597>.
- [5] Chiriac, F.L.; Paun, I.; Iancu, V.I.; Pirvu, F.; Dinu, C.; Niculescu, M.; Petre, V.A. Fate of pharmaceutical residue in two Romanian rivers receiving treated water: Occurrence, distribution and risk assessment, *Sci. Total Environ.* **2024**, *923*, <https://doi.org/10.1016/j.scitotenv.2024.171359>.
- [6] Musfira Shabbirahmed, A.; Jacob, A.; Dey, P.; Somu, P.; Haldar, D. Biomass as eco-friendly adsorbents for the removal of emerging pollutants from wastewater: A review, *Discov. Appl. Sci.* **2025**, *7*, <https://doi.org/10.1007/s42452-025-07463-7>.
- [7] Karić, N.; Maia, A.S.; Teodorović, A.; Atanasova, N.; Langergraber, G.; Crini, G.; et al. Bio waste valorisation: Agricultural wastes as biosorbents for removal of (in)organic pollutants in wastewater treatment. *Chem. Eng. J. Adv.* **2022**, *9*, 100239, <https://doi.org/10.1016/j.cej.2021.100239>.
- [8] Razzak, N.R.B.; Syeda, H.I.; Milne, N.A.; Moon, E.M. Turning municipal food organic waste into activated carbon: A step towards circular economy. *Therm. Sci. Eng. Prog.* **2024**, *56*, 103073, <https://doi.org/10.1016/j.tsep.2024.103073>.
- [9] Wada, O.Z.; Olawade, D.B. Recent occurrence of pharmaceuticals in freshwater, emerging treatment technologies, and future considerations: A review. *Chemosphere* **2025**, *374*, 144153, <https://doi.org/10.1016/j.chemosphere.2025.144153>.
- [10] Al-Sareji, O.J.; Grmasha, R.A.; Meiczinger, M.; Al-Juboori, R.A.; Somogyi, V.; Stenger-Kovács, C.; Hashim, K.S. A sustainable and highly efficient fossil-free carbon from olive stones for emerging contaminants removal from different water matrices. *Chemosphere* **2024**, *351*, 141189, <https://doi.org/10.1016/j.chemosphere.2024.141189>.
- [11] Ghosh, S.; Pramanik, K. Extraction of lignin from sustainable lignocellulosic food waste resources using a green deep eutectic solvent system and its property characterization. *Int. J. Biol. Macromol.* **2025**, *307*, 142094, <https://doi.org/10.1016/j.ijbiomac.2025.142094>.
- [12] Mounika, T.; Reddy, A.V.B.; Madhavi, V.; Devi, K.S. Eggshell-Based Biochar for Superior Adsorption of Crystal Violet Dye and Fluoride from Wastewater. *Asia-Pac. J. Chem. Eng.* **2026**, *21*, <https://doi.org/10.1002/apj.70160>.
- [13] Liu, Y.; He, Z.; Uchimiya, M. Comparison of biochar formation from various agricultural by-products using FTIR spectroscopy. *Mod. Appl. Sci.* **2015**, *9*, 246–253. <https://doi.org/10.5539/mas.v9n4p246>.
- [14] Jahanban-Esfahlan, A.; Jahanban-Esfahlan, R.; Tabibiazar, M.; Roufegarinejad, L.; Amarowicz, R. Recent advances in the use of walnut (*Juglans regia* L.) shell as a valuable plant-based biosorbent for the removal of hazardous materials. *RSC Adv.* **2020**, *10*, 7026–7047. <https://doi.org/10.1039/C9RA10084A>.
- [15] Sampaio, S.L.; Petropoulos, S.A.; Alexopoulos, A.; Heleno, S.A.; Santos-Buelga, C.; Barros, L.; Ferreira, I.C.F.R. Potato peels as sources of functional compounds for the food industry: A review. *Trends Food Sci. Technol.* **2020**, *103*, 118–129. <https://doi.org/10.1016/j.tifs.2020.07.015>.
- [16] Zhuang, Z.; Liu, Y.; Wei, W.; Shi, J.; Jin, H. Preparation of biochar adsorption material from walnut shell by supercritical CO₂ pretreatment. *Biochar* **2024**, *6*, Article 11. <https://doi.org/10.1007/s42773-024-00302-9>.
- [17] Raji, Z.; Maleka, R.; Karim, A.; Karam, A.; Aider, M.; Khalloufi, S. Biosorption of lead from water using fruit and vegetable peels: Characteristics, adsorption kinetics, and isotherms. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 15775–15790. <https://doi.org/10.1007/s13762-024-06089-z>.
- [18] Yunus, Z.M.; Gidado, Y.; Al-Gheethi, A.; Othman, N.; Hamdan, R.; Ruslan, N.N. Advanced methods for activated carbon from agriculture wastes: A comprehensive review. *Int. J. Environ. Anal. Chem.* **2022**, *102*, 134–158. <https://doi.org/10.1080/03067319.2020.1722816>.

- [19] Davidraj, J.M.; Sathish, C.I.; Benzigar, M.R.; Li, Z.; Zhang, X.; Bahadur, R. Recent advances in food waste-derived nanoporous carbon for energy storage. *Sci. Technol. Adv. Mater.* **2024**, *25*, 2357062. <https://doi.org/10.1080/14686996.2024.2357062>.
- [20] Zhuo, G.H.; Xue, D.X.; Huang, L.F.; Wang, Q.; Zhu, G.; Wang, C.Y. Adsorption of phosphates on a novel eggshell Ca-modified anaerobic sludge-based biochar: Adsorption performance and mechanism. *PLoS One* **2025**, *20*, e0337183. <https://doi.org/10.1371/journal.pone.0337183>.
- [21] Albatrni, H.; Qiblawey, H.; Al-Marri, M.J. Walnut shell based adsorbents: A review study on preparation, mechanism, and application. *J. Water Process Eng.* **2022**, *45*, 102527. <https://doi.org/10.1016/j.jwpe.2021.102527>.
- [22] Aziz, K.H.H.; Mustafa, F.S.; Hassan, M.A.; Omer, K.M.; Hama, S. Biochar as green adsorbents for pharmaceutical pollution in aquatic environments: A review. *Desalination* **2024**, *583*, 117725. <https://doi.org/10.1016/j.desal.2024.117725>.
- [23] Deshmukh, S.M.; Dhokpande, S.R.; Sankhe, A.A.; Khandekar, A.R. Bio adsorbents properties for waste treatment: A review. *Int. J. Environ. Waste Manag.* **2026**, *39*, 327–356. <https://doi.org/10.1504/IJEW.2026.153406>.
- [24] Varela, C.F.; Moreno-Aldana, L.C.; Agámez-Pertuz, Y.Y. Adsorption of pharmaceutical pollutants on ZnCl₂-activated biochar from corn cob: Efficiency, selectivity and mechanism. *J. Bioresour. Bioprod.* **2024**, *9*, 58–73. <https://doi.org/10.1016/j.jobab.2023.10.004>.
- [25] Murtaza, G.; Ahmed, Z.; Dai, D.Q.; Iqbal, R.; Bawazeer, S.; Usman, M.; et al. A review of mechanism and adsorption capacities of biochar-based engineered composites for removing aquatic pollutants from contaminated water. *Front. Environ. Sci.* **2022**, *10*, 1035865. <https://doi.org/10.3389/fenvs.2022.1035865>.
- [26] Ngole-Jeme, V.M.; Ntumba, C.N. Fruit and vegetable peel characteristics and their conversion to biosorbents using hydrothermal carbonization and pyrolysis: A review. *BioResources* **2024**, *19*, 9853–9904. <https://doi.org/10.15376/biores.19.4.Ngole-Jeme>.
- [27] Karim, A.; Raji, Z.; Karam, A.; Khalloufi, S. Valorization of fibrous plant-based food waste as biosorbents for remediation of heavy metals from wastewater—A review. *Molecules* **2023**, *28*, 4205. <https://doi.org/10.3390/molecules28104205>.
- [28] Bharat, S.; Manchanda, D. Efficient bio adsorbents for removal of heavy metals from water: A review. *Int. J. Chem. Stud.* **2017**, *5*, 1691–1694.
- [29] Aslan, S.; Sirazi, M. Adsorption of sulfonamide antibiotic onto activated carbon prepared from an agro-industrial by-product as low-cost adsorbent: Equilibrium, thermodynamic, and kinetic studies. *Water Air Soil Pollut.* **2020**, *231*, 222. <https://doi.org/10.1007/s11270-020-04597-1>.
- [30] Juella, D.M. Promising adsorptive materials derived from agricultural and industrial wastes for antibiotic removal: A comprehensive review. *Sep. Purif. Technol.* **2022**, *284*, 120286. <https://doi.org/10.1016/j.seppur.2021.120286>.
- [31] Tang, K.H.D. Valorization of organic waste as biosorbents for wastewater treatment. *Water Emerg. Contam. Nanoplastics* **2024**, *3*, 38. <https://doi.org/10.20517/wecn.2024.38>.
- [32] Afolabi, F.O.; Musonge, P.; Bakare, B.F. Evaluation of lead (II) removal from wastewater using banana peels: Optimization study. *Pol. J. Environ. Stud.* **2022**, *30*, 1487–1496. <https://doi.org/10.15244/pjoes/124250>.
- [33] Abbas, M.; Nussrat, T. Statistical analysis of experimental data for adsorption process of cadmium by watermelon rinds in continuous packed bed column. *Int. J. Innov. Creat. Change* **2020**, *13*, 1104–1121.
- [34] Alfattani, R.; Shah, M.A.; Siddiqui, M.I.H.; Ali, M.A.; Alnaser, I.A. Bio-char characterization produced from walnut shell biomass through slow pyrolysis: Sustainable for soil amendment and an alternate bio-fuel. *Energies* **2022**, *15*, 1. <https://doi.org/10.3390/en15010001>.