Development of Bio adsorbents for the Adsorption/Recovery of Precious Metals

Tamara Govindsamy, Willie Nheta

Abstract**—** Decades of intensive mining have led to the rapid depletion of readily processed sulphide platinum group metal (PGM) ores, driving growing interest in the exploitation of oxidized PGM resources. Current estimates indicate that more than 500 million tonnes of oxidized PGM ores exist globally, largely as stockpiles, unmined deposits, or tailings. To meet sustained global demand for PGMs, it is essential to develop effective processing strategies for these near-surface oxidized ores. Oxidized PGM ores form through the weathering of primary sulphide ores upon exposure to air and water, resulting in complex mineralogical transformations that hinder conventional recovery methods. Traditional sulphide flotation techniques are ineffective for these ores, as recovery relies on the balance of hydrophobic and hydrophilic species on mineral surfaces, conditions that are significantly altered during oxidation. Consequently, alternative processing approaches are required for the treatment of these low-grade, refractory materials. Hydrometallurgical processing offers a promising route, particularly through leaching, which enables the direct dissolution of precious metals from complex oxidized matrices. However, efficient downstream recovery of dissolved metals remains a critical challenge. This study addresses this gap by developing an environmentally sustainable and highly selective adsorbent for platinum and gold recovery. The research investigates the synthesis and performance of functionalized biochar derived from locally sourced macadamia nutshells. The biomass was cleaned, dried, and pyrolyzed at 550–650 °C to produce a porous carbonaceous material with a high internal surface area. The resulting biochar was chemically modified using hydrogen peroxide to introduce oxygen-containing functional groups, thereby enhancing its surface reactivity and charge characteristics for targeted metal adsorption. Adsorption experiments were conducted using 100 ppm solutions of gold and platinum, with 1 g of functionalized biochar. Kinetic studies over 1–60 minutes revealed rapid adsorption within the first 30 minutes, after which equilibrium was reached. The biochar demonstrated high adsorption efficiencies, achieving approximately 85% recovery for gold and 78% for platinum at pH 2.

This study highlights the dual benefits of the approach: improving hydrometallurgical recovery from difficult oxidized PGM ores while valorizing agricultural waste into high-value adsorbents. The findings suggest that functionalized macadamia biochar is a promising, sustainable material for precious metal recovery, supporting both resource efficiency and environmental stewardship in the mining sector.

Index Terms— Oxidized PGM ores, Biochar adsorbent, Metal adsorption, Gold and platinum recovery, Sustainable processing.

I. Introduction

Platinum Group Metals commonly platinum, rhodium, palladium, ruthenium, iridium and osmium are significant due to their exceptional corrosion resistance, catalytic activity, high melting points and suitability for electronic applications and medical devices or equipment. Recent ventures in hydrogen electrolysers make PGMs vital for recovery and show value addition to the world supply. To meet the world's demand of PGMSs, it is necessary to recover these metals from low grade and complex sources that need to be explored and treated [1,2].

South Africa remains the leading country in the supply of PGEs to the world and dominant in the mining industry as the source of PGEs being the Bushveld Igneous Complex, followed by Russia, Zimbabwe and Canada. PGEs have been labelled as 'Critical metals'' due to their elemental role in significant modern technologies used worldwide. [3]

There has been a great shift in exploring the recovery oxidized PGM ores due to fast depletion of sulphide PGM bearing minerals and exceeding 500 tonnes of oxidized PGM ores that are either stockpiled, unmined or discarded as waste in South Africa and Zimbabwe.[4]

It has been observed that treating these oxidized PGM ores by conventional methods such as flotation has resulted in low recoveries due to surface oxidation of sulphide minerals that affect the recovery during the flotation. Therefore, creating an opportunity to explore alternative processing techniques which can treat low grade oxidized ores effectively. Poor recoveries of oxidized PGMs by conventional flotation has resulted in investigating complementary processing routes such as pyrometallurgical, hydrometallurgical and other technologies as a solution. [5-6].

Hydrometallurgical routes have gained popular interest as an alternative processing route for oxidized PGM ores whilst using adsorption as a method of recovery of Platinum and Gold from dilute solutions from leaching processes. Adsorbents have a greater surface area and chemistry that make them ideal to fine tune for successful adsorption of precious metals from dilute solutions. [7]

This study focused on investigating the development of a sustainable and environmentally friendly adsorbent from macadamia nutshells and functionalizing it to enhance its

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reactivity and adsorption behavior whilst observing its efficiencies.

II. Materials And Methods

A. Adsorbent characterization and preparation

Raw macadamia nutshells were sourced locally as a product of agricultural waste from the Limpopo region, South Africa and thereafter cleaned, washed and dried before being pyrolyzed at temperatures between 550-650 degree Celsius to obtain a macadamia biochar that is highly porous and has a greater surface area. Thereafter a solution of 5-10% strength of hydrogen peroxide was formulated to functionalize the newly formed biochar to introduce functional groups. Thereafter chemical characterization was done on the adsorbent before functionalization and after to observe the transformation and effect of enhancement of the adsorbent.

B. Adsorption experimental

Adsorption tests used 1g of adsorbent dispersed in 100ppm of gold and platinum solution in a shaking reactor. The variables investigated were pH (1-6), contact time (1-60 minutes), adsorbent dosage (0.5g-2g) and temperature (25- 60). The adsorption performance was assessed by the uptake of the platinum and gold concentration. Non- linear pseudo -first order (PFO) and pseudo-second order (PSO) kinetic models were fitted to the data.

III. Results And Discussion

A. FTIR Functional Groups results

The raw macadamia nutshell biomass was analyzed with FTIR equipment to determine the functional groups, and the results are shown in Fig.1. Functional groups such as hydrocarbon chains, hydroxyl, carboxyl and carbonyls were identified in the sample. The macadamia biomass results show the occurrence of a peak in the diagnostic region at approximately 3421.86cm^{-1} wavelength. The transmittance table for FTIR results interpretation shows this wavelength strongly indicates the presence of -OH bonds, which is the functional group for hydroxyls, as well as the presence of C-H bonds in the region of 2926.87cm^{-1}, which is the functional group for hydrocarbons. It can be concluded that the functional groups are in alignment with the organic nature of lignocellulosic components found in biomass [10].

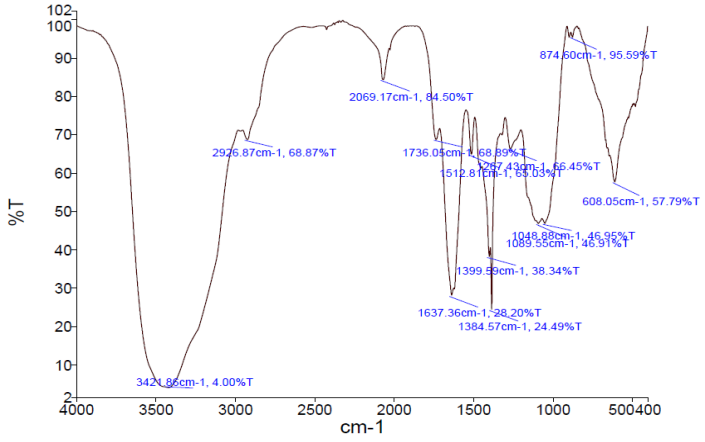


Fig. 1 FTIR spectra of macadamia biomass before Pyrolysis.

The FTIR spectrum (Fig. 2) shows the functional group present and what was formed after functionalization.

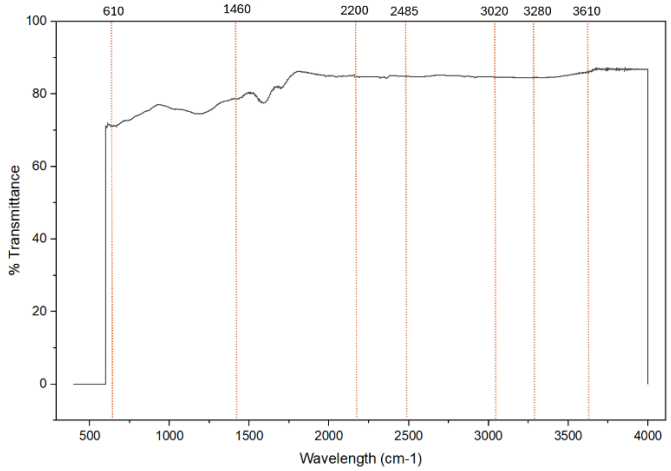


Fig. 2: FTIR spectra of functionalized macadamia biochar.

The Fig.2 FTIR spectrum exhibited characteristic adsorption bands at 610, 1460, 2200, 2485, 3020, 3280 and 3610 cm^{-1}. The band at 610 cm^{-1} is attributed to sulfur-containing functionalities (C-S and C-O vibrations), confirming successful surface modification. The band at 1460cm^{-1} corresponds to carboxylate and aromatic skeletal vibrations, while the band at 2200cm^{-1} is assigned to nitrile (C≡N) groups. The band at 2485cm^{-1} is associated with the hydrogen-bonded carboxylic acid O-H vibrations. Bands observed at 3020cm^{-1} arise from the aromatic C-H stretching, whilst the broad bands at 3280 and 3610cm^{-1} are attributed to hydroxyl and amine functionalities. The thermal degradation creates a highly porous structure with a large specific surface area that is crucial for good adsorption.

These oxygen-, sulfur- and nitrogen- containing surface groups provide active sites applicable for metal adsorption through electrostatic interactions, surface complexation and chemisorption mechanisms. Enhancing the affinity of the biochar towards the precious metal complexes.

B. Surface topography of the macadamia nutshells

The Fig. 1 shows the surface of a raw macadamia nutshell that is composed of irregular, angular particles with a dense, rough texture and limited visible porosity. This structure is typical for unprocessed lignocellulosic biomass. This was further supported by the SEM-EDS results indicating the surface is dominated by carbon (59.86 wt%) and oxygen (39.26 wt%), aligning with the organic nature of biomass composed of cellulose, hemicellulose, and lignin.

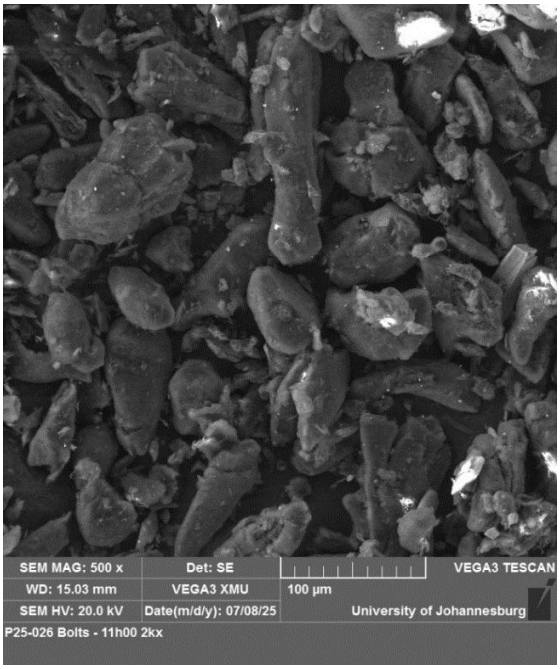


Fig. 3: Morphology results of macadamia material before pyrolysis.

Fig. 4 shows the SEM analysis results that reveal a further maturation of the porous structure, where the biochar maintains its highly developed porosity while exhibiting a more organized and refined pore structure compared to the Fig. 3. Furthermore, it shows a surface that has undergone near-complete carbonization, with the development of a well-defined porous architecture that is more refined and consolidated than that of Fig.3. Elemental composition reflects this advanced carbonization, with carbon content peaking at 92.20 wt%, while oxygen content drops dramatically to just 7.51 wt%. This agrees with the FTIR spectrum (Fig. 2), which shows loss in functional groups due to thermal degradation, which leads to dehydration and carbonization.

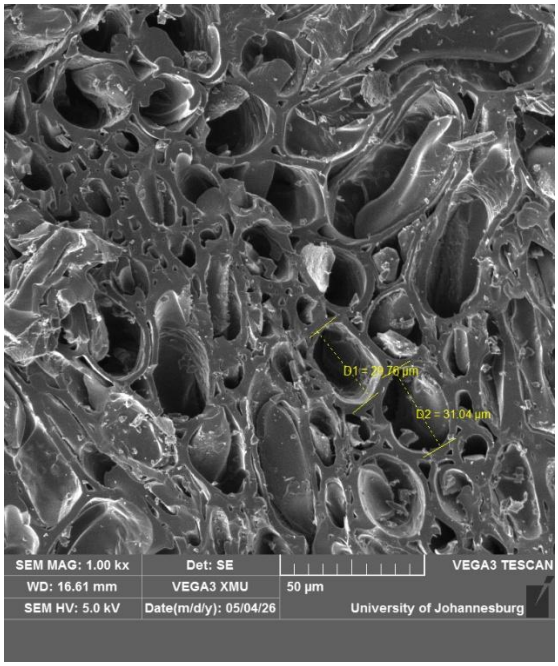


Fig. 4: Morphology results of a functionalized macadamia material.

C. Brunauer Emmett Teller (BET) surface area analyser

The sample was analysed using BET and the results are shown in Table I. During the pyrolysis stage, at 650 degrees Celsius, the macadamia biochar showed highly porous and has a greater surface area, with 266.87 m^2/g of the total surface are associated with micropores, which is advantageous for the adsorption of dissolved Au and Pt species. The average pore diameter remained in the mesoporous range (2.26nm), indicating that the pore structure was largely preserved after functionalization. The high BET specific surface area indicates that the macadamia biochar formed a highly porous stage due to the pyrolysis temperature increase and maximizes the available sites for adsorption. Mesopores are excellent for providing fast transport channels, allowing for adsorbate molecules to quickly diffuse through the biochar and result in high adsorption capacity and fast adsorption [7]. A 71.57% microporous contribution indicates that most of the available surface area resides inside pores smaller than 2nm (micropores), while only 28.44% is associated with the external surface and larger pores. The BET results are in agreement with the SEM-EDS results, as an increase in surface area as the temperature rises, as witnessed during the pyrolysis stage. Furthermore, they also correspond with the SEM imaging of a highly porous structure developing as the temperature rises.

TABLE I
THE SURFACE AREA ANALYSER RESULTS

Sample	BET Surface Area (m^2/g)	Micropore Area (m^2/g)	Pore Volume (cm^3/g)	Average Pore Diameter (nm)
Functionalized BC	372.88	266.87	0.21073	2.26

D. Adsorption and Adsorbent Performance

Adsorption experiments were conducted using 100 ppm solutions of gold and platinum, with 1 g of functionalized biochar and the results are shown in Table II and III. Kinetic studies over 1–60 minutes revealed rapid adsorption within the first 30 minutes, after which equilibrium was reached. The biochar demonstrated high adsorption efficiencies, achieving approximately 85% recovery for gold and 78% for platinum at pH 2. The adsorption performance achieved for gold at pH 2 should be regarded as an optimal operating region for the specific system investigated rather than a universal optimal condition for all adsorption processes. Variations in solution chemistry, metal ion concentrations and gold-complex speciation can substantially affect both adsorption kinetics and equilibrium adsorption capacity as a result of the adsorbate concentration and available adsorption sites.

TABLE II
NON-LINEAR ADSORPTION KINETIC PARAMETERS (AU)

Kinetic model	**k**	**q_e, exp (mg/g)**	**R^2**
PFO, non-linear	0.068	85.90	0.992
PSO, non-linear	0.00155	88.14	0.994

The nonlinear pseudo-second-order model provided a slightly superior fit to the Au adsorption results as compared to pseudo-first-order model (R^2 = 0.994 versus 0.992). The results indicate that the Au adsorption onto the functionalised biochar proceeds rapidly and is likely governed by the surface interactions between Au species and the functional present on the biochar surface. The excellent fit of each model suggests that more than one adsorption may contribute to the overall adsorption behaviour.

TABLE III
NON-LINEAR ADSORPTION KINETIC PARAMETERS (PT)

Kinetic model	**k**	**q_e, exp (mg/g)**	**R^2**
PFO, non-linear	0.050	79.00	0.991
PSO, non-linear	0.00110	88.14	0.993

The nonlinear pseudo-second-order model provided a slightly superior fit to the Pt adsorption results compared with the pseudo-first-order model. The results indicate that Pt adsorption onto the functionalised biochar proceeds rapidly and is likely governed by surface interactions between Pt species and the functional groups present on the biochar surface. The excellent fit of both models suggests that multiple adsorption mechanisms may contribute to the overall adsorption behaviour, with adsorption occurring through the progressive occupation of available active sites on the biochar.

IV. CONCLUSION

The results demonstrate that hydrogen peroxide-functionalized macadamia nutshell biochar is an effective and environmentally sustainable adsorbent for the recovery of precious metals from hydrometallurgical solutions. High adsorption efficiencies of approximately 85% for gold and 78% for platinum were achieved at pH 2, with rapid adsorption kinetics and equilibrium attained within 30 minutes. These findings confirm the potential of functionalized biochar as a low-cost and selective recovery medium for dissolved precious metals. By combining agricultural waste valorization with improved metal recovery, this approach offers a promising pathway for the sustainable processing of oxidized PGM ores and supports the development of greener, more resource-efficient technologies for the future of the PGM industry.

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