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RESEARCH ARTICLE

# Thermal and Elemental Analysis of Coconut Shell Powder as a Nature-Friendly Sustainable Material

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## ABSTRACT

Coconut Shell Powder (CSP) is a biodegradable lignocellulosic biomass material derived from coconut shells and comprising principally cellulose, hemicellulose, and lignin. We characterize elemental and thermal properties of CSP to assess its viability as a nature-based material for agricultural and engineering use. CHSO elemental analysis conducted on the CSP using a LECO CS744 and ONH836 revealed meaningful levels of carbon (40.1 to 42.1%), hydrogen (19.6 to 20.2%), and oxygen (33.3 to 34.7%) proved organic in character and of biomass origin, and a small amount of sulfur (0.084 to 0.090%) suggests that the material may be compatible with the environment to alleviate corrosion and soil acidification. Thermogravimetric analysis (TGA) under nitrogen, modified to report on TGA results, provides empirical evidence for a three-stage thermal degradation behavior of the material. Initially, moisture loss exists in the range of 50 to 150 °C (6.097%), and the degradation of hemicellulose, cellulose, and lignin all occur in the range of 156 to 655 °C (75.369%). A small proportion of the material residue retained in a stabilized state after thermal degradation was found to be 18.291% at 650 °C. All observations were consistent with the literature performance of CSP, which defines its thermal stability and behavior. The elemental and thermal properties collectively confirmed the multipurpose potential for CSP. As a soil amendment, CSP is claimed to be a slow-release material to the soil and improves soil moisture retention. In support of engineering applications, CSP could have potential as a natural filler, an abrasive material, and a provider of insulation from thermal transfers. Overall, CSP is an adaptive material laying the foundations for sustainable innovation in environmentally friendly applications for human use.

**Keywords**: *Coconut Shell Powder (CSP), Thermogravimetric Analysis (TGA), CHSO elemental analysis, Lignocellulosic biomass, Sustainable material, Eco-friendly applications*

## INTRODUCTION

Coconut Shell Powder (CSP) is a lignocellulosic biomass material sourced from the hard endosperm of coconuts, and is an abundant, renewable, and environmentally-friendly resource, F. Vieira *et al.,* With a molecular structure of cellulose, hemicellulose, and lignin, the material has embedded mechanical properties, thermal stability, and high organic carbon content for usages in a wide variety of industries, including: agriculture, engineering, and environmental management. As a nature-friendly material, CSP is a biodegradable, non-toxic, and sustainable substitute for synthetic materials across multiple applications, R. Arun *et al.,* The elemental composition of CSP analyzed via CHSO analysis is essential for

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understanding the nature of the chemical, thermal, and mechanical properties, where the high carbon and oxygen content provide structural integrity and develop the ability to undergo controlled thermal degradation, while low sulfur content and trace nitrogen limit the environmental effect and suitability of soil uses, C. Liyanage *et al.,* and T. Rout *et al.,*

Thermogravimetric analysis (TGA) provides additional information regarding the thermal stability of the material and the overall multi-stage degradation pattern corresponding to the stepped burning of hemicellulose, cellulose, and lignin. The consistent thermal behavior and relatively high char yield further support the potential use of CSP as a sustainable option for soil amendment, biochar sources, and the upgrading of materials involving reinforcement in composite products or as a building material.

The multipurpose features of CSP facilitate the transition from sustainable agriculture to engineering, C. Ngah *et al.,* For agricultural purposes, it improves growth by increasing) soil fertility, moisture retention, and microbial health, and for engineering purposes, it provides a natural abrasive, filler, or heat insulator, C. Ngah *et al.,* and A. A. Okoya *et al*.,

This twofold usage makes CSP a highly regarded eco-friendly product capable of advancing sustainability, providing eco-friendly materials with a lower impact on the environment, and achieving circular economy values.

The summary of the elemental and thermal characterization indicates that CSP can be used in varying capacities in industrial and agricultural applications. Actual characterization is essential because each component and thermal characteristic provides insight into the practical application of CSP.

Coconut Shell Powder (CSP) is a natural, sustainable product derived from coconut shells. CSP has wall tissue structure that is composed mainly of cellulose, hemicellulose, and lignin, which give it strength and heat resistance. CSP holds very little moisture at sustained temperatures (Ngah et al., 2014), and the constituents of CSP have predictable degradation temperatures (180-350 degrees Celsius), which leads to many applications, including biochar, thermal insulation, and energy recovery, S. N. Fayyadh *et al*.,

The composition of CSP is essential for its diversity of applications. Okoya et al. (2020) reported that coconut shell char has more than 60% carbon content, which indicates an exceptionally high organic carbon content. Rout *et al.,* (2013) and Fayyadh *et al.,* (2025) also observed elevated carbon values in CSP.

CSP is useful as an abrasive of natural origin, as a filler in composites, and as a slow-release fertilizer, A. A. Okoya *et al.,* CSP contains low sulfur content, which helps to minimize corrosion of heat exchangers and to reduce soil acidification. Carbon-containing compounds, such as hydrogen and oxygen in the CSP sample, indicated that CSP is produced from a natural, biodegradable source.

The thermal properties of CSP also support this same multi-step breakdown behavior. Liyanage & Pieris (2015) reported that cellulose breakdown was about 338 °C, with about 16-25% residual char remaining, K. H. Yeong *et al.,* In the present study, the CSP residual mass was 18.291%, suggesting comparable results. Andezai et al. (2020) also observed slow breakdown for lignin at high temperatures, further indicating the heat stability of CSP, A. A. G. Fernando *et al.,*

To sum up findings from the preceding research, CSP appears to be a safe, high-carbon, and eco-friendly material with a variety of potential uses, including improving soil structure, enhancing water retention, increasing biological capacity for agriculture, and serving as an abrasive, filler, and insulating material for engineering applications. The thermal behavior align with previous findings, indicating that CSP can be a reliable and sustainable raw material for eco-friendly uses.

## MATERIALS AND METHODS

Coconut Shell Powder (CSP) was selected as a test case material in this study. The CSP was obtained as pre-ground from a local vendor in Lucknow, Uttar Pradesh, India, to facilitate easy exploration, information acquisition, and tracing of the source for supply and quality assurance. The powder was exceptionally well-prepared as a very fine, ground powder of uniform size, so the coconut shell powder did not require additional grinding or milling operations. The high-grade coconut shell powder used to conduct the study is shown in Figure 1.

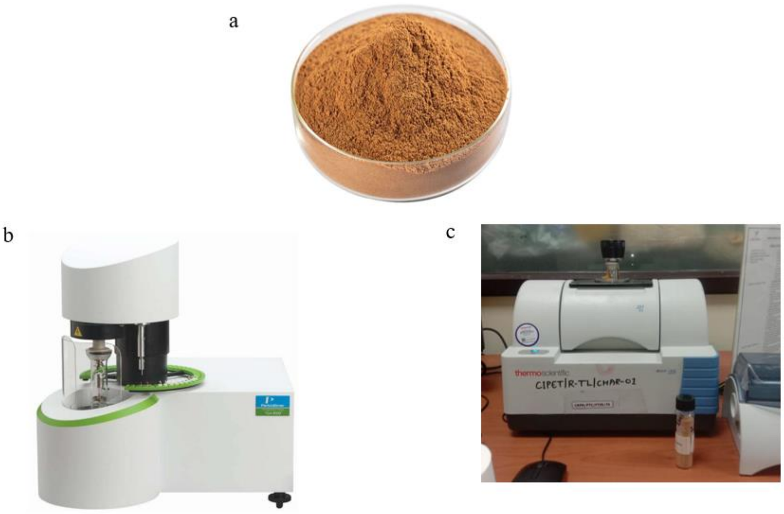

**Figure 1: Coconut Shell Powder sample, along with the TGA and FTIR instruments**

Before carrying out any analyses using the coconut shell powder, the powder was kept in a sealed environment to minimize the likelihood of contamination from the surrounding atmosphere and moisture absorption. Then, the powder was kept in a sealed container to maintain its properties and potential. Then, a visual examination was conducted to ensure the cleanliness, homogeneity, and uniformity of the powder, confirming it would have sufficient properties to be characterized beyond its uses in this study.

### *2.1. Thermogravimetric Analysis (TGA)*

Thermogravimetric Analysis (TGA) was used to investigate the thermal degradation and decomposition of the CSP in an inert atmosphere. This investigation allows for the examination of sample weight loss as a function of temperature, revealing specific stages of decomposition due to the loss of hemicellulose, cellulose, and lignin.

### *2.2 CHSO Elemental Analysis*

The elemental makeup of Coconut Shell Powder (CSP) was evaluated using analysers LECO CS744 and ONH836 at SAIF, IIT Madras (Chennai 600036). Each run of the analysis used approximately 20mg of powdered sample and gained proportions of Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S), and Oxygen (O) while establishing the organic and lignocellulosic nature of CSP.

With carbon, the LECO CS744 Analyzer also measured sulfur in the presence of various inorganic and carbonaceous materials. The sample is burned in oxygen , and the carbon and sulfur are produced as carbon dioxide and sulfur dioxide gases. These gases are detected by infrared absorption methods,

**Table 1: Parameters Used for TGA**

| S.No | Parameter | Details |
|---|---|---|
| 1 | Material | Coconut Shell Powder (CSP) |
| 2 | Sample Preparation | Ball-milled after grinding |
| 3 | Sample Weight | 20 mg |
| 4 | Heating Rate | 10 °C per minute |
| 5 | Temperature Range | 50 °C to 650 °C |
| 6 | Atmosphere | Nitrogen ($N_2$) |
| 7 | Gas Flow Rate | 20 ml/min |
| 8 | Crucible Type | Platinum |
| 9 | Standard Followed | ASTM E1131 |

providing mass-percent concentrations. The mass measurement range using the analyzers is 0.002-60mg (C) and 0.002-17.5mg (S) per 1g of sample.

With oxygen, nitrogen, and hydrogen, the LECO ONH836 Analyzer quantified in the presence of inert helium, leading to the production of carbon monoxide, nitrogen gas, and hydrogen gas, which are detected using an infrared sensor and thermal conductivity. The mass measurement ranges using the analyzers are 0.00005-50mg (O), 0.00005 -30mg (N), and 0.0001-2.5mg (H) per 1g of sample.

## RESULTS AND DISCUSSION

### *3.1. Thermogravimetric Analysis (TGA) of Coconut Shell Powder (CSP)*

Thermogravimetric analysis (TGA) of coconut shell powder (CSP) was performed in an inert nitrogen atmosphere to evaluate its thermal degradation behavior. The TGA analyses indicated the typical multiple degradation stages associated with lignocellulosic biomass, displaying CSP's thermal degradation behavior (Figure 2). The test was conducted at a heating rate of 10 °C/min from 50 °C to 650 °C. The analyses revealed three identifiable thermal degradation stages corresponding to the decomposition of hemicellulose, cellulose, and lignin, the primary organic fractions of CSP.

During the first stage (50-150 °C), CSP experienced a negligible weight loss of 6.097%, primarily due to evaporating physically bond water and volatile organic compounds with low boiling points. There were no indications of chemical decomposition, demonstrating that the material is thermally stable when heated at a moderate level. This first phase, labeled as the drying stage, shows CSP's ability to survive in low to moderately high temperature environments, for applications and situations where heating could be mild.

The second stage, named active pyrolysis, covered the approximated temperature range of 156.07 °C to 655.37 °C, where the material showed a significant weight loss of 75.369%. This second stage of mass loss corresponds to the sequential thermal degradation of hemicellulose, cellulose, and lignin. The thermal degradation of hemicellulose begins at a lower temperature range. A small shoulder shows some physical evidence of hemicellulose decomposition in the TGA curve at around 200 °C. Cellulose decomposes rapidly due to thermal degradation, showing a large peak around 300 °C. This provides evidence that cellulose has crystalline properties that undergo thermal degradation rapidly and indiscriminately. Lignin has a more complex control over thermal degradation, as it is an aromatic macromolecule that

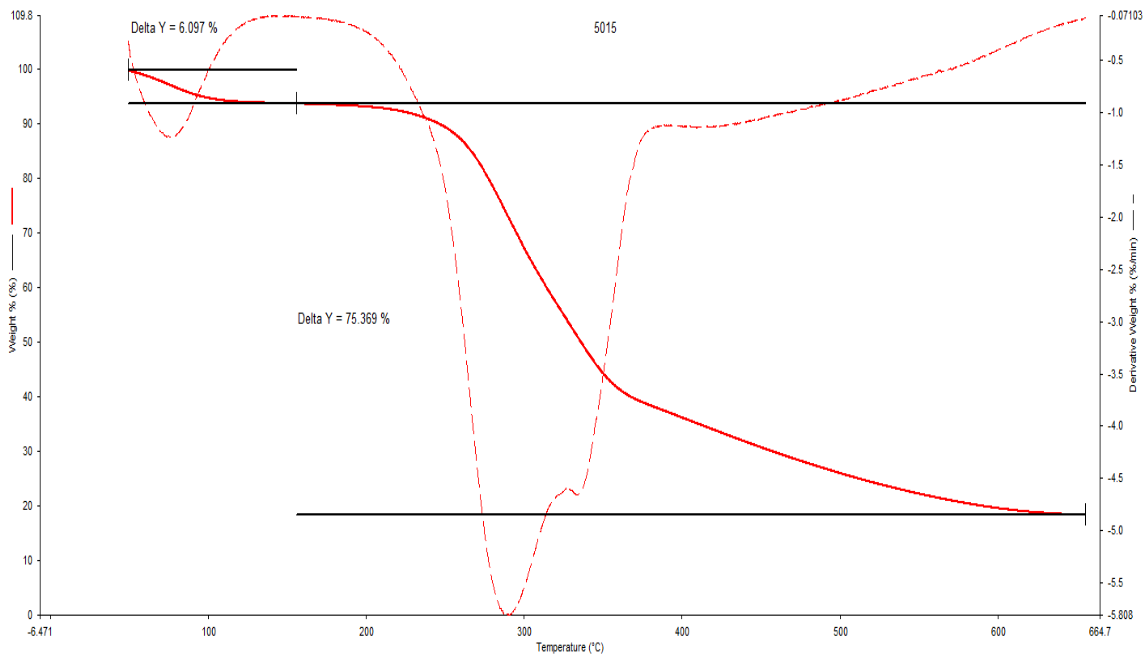


**Figure 2: Thermogravimetric Analysis (TGA) graph of Coconut Shell Powder.**

degrades slowly over a temperature range of around 350 °C to 500 °C. The slow thermal degradation and significant mass loss indicate that lignin is thermally stable and contributes to residues in the char.

The last stage, noted at 650 °C, demonstrated a residual mass of 18.291%, mainly consisting of char and inorganic ash, indicative of stable carbonaceous material. This residual formation stage demonstrates that CSP generates a significant amount of thermally stable residues under conditions used for pyrolysis. The TGA data for CSP is summarized in Table 2.

Analysis of the results obtained through the stages of pyrolysis revealed that the drying stage occurs due to moisture evaporating, while the active pyrolysis phase signifies the rapid thermal decomposition of cellulose and the slower degradation of the lignin component. The stage of residual formation highlights the occurrence of considerable amounts of char, facilitating high thermal and mechanical stability. Comparisons to the existing literature also showed a good agreement. For instance, Ngah *et al.,* (2014) showed similar moisture losses below 150 °C and significant degradation of hemicellulose between 200–350 °C, S. N. Fayyadh *et al.,* The authors also reported a peak degradation of cellulose (336 °C, similar to 338 °C in this study) and a flexible char residual, characterized between 16–25%, which corresponds well to the current result of 18.291%. Rout *et al.,* (2013) and Andezai *et al.,* (2020) also confirmed that pyrolysis follows a slow degradation of lignin, with thermal resistances up to 500–900 °C, identifying CSP's stability as a highly reliable lignocellulosic biochar, B. Edun *et al.*, and A. A. G. Fernando *et al.,*

**Table 2: Thermogravimetric Data Summary for Coconut Shell Powder**

| S No. | Temperature Range (°C) | Observed Mass Loss (%) | Interpretation |
|---|---|---|---|
| 1 | 50 – 150 | 6.097 | Loss of moisture and low-boiling volatiles |
| 2 | 156.07 – 655.37 | 75.369 | Decomposition of hemicellulose, cellulose, lignin |
| 3 | Residual Mass at 650 °C | 18.291 | Char and ash (thermally stable residue) |

Overall, the consistent multi-phase decomposing behavior of CSP demonstrated the stability of a lignocellulosic material, with predictable thermal degradation, i.e., as demonstrated in thermogravimetric analysis (TGA), which displays a controlled reaction with minimal weight loss in the early stages of decomposition, indicating minimal exothermic events in the inert atmosphere in this study. The character of stability also indicates that CSP should be easily handled in thermochemical, pyrolytic, and energy-related applications, while still allowing for an efficient biomass char production. The summary of thermal results and substantial residual weight highlights the stability of CSP subjected to moderate to high temperatures, without degradation of structural integrity, making it ideally suited for a wide range of applications.

In agriculture, CSP's high level of carbon and structural integrity allows it to function as a slow-release organic soil amendment to improve soil fertility, water-retention capacity, and greater overall soil health in a sustainable manner, C. Ngah *et al.,* and R. K. Rajamony *et al.*, Its predictable thermal behavior means that it can be released gradually, which has implications for longer-lasting effects to enhance soils. In engineering, CSP's mechanical hardness and thermal stability are applicable not only as a natural abrasive associated with AJM processes but also in thermal insulation composites, biochar, filler applications in polymer composites, and green construction materials. The dual-purpose characteristics of CSP, both as a sustainable agricultural input and as an engineering material resource, support its position as an environmentally conscious and multifunctional material. The material's strength of performance is applicable in thermal, mechanical, and chemical applications, making it an attractive prospect as an innovative solution for applications that prioritize sustainability and functionally efficient performance, C. Fragassa *et al.,*

The multifunctional potential of CSP for agriculture and engineering is not unique to this study. Fayyadh et al., (2025) found that coconut shell biochar has a high carbon content and stable structure, improving soil fertility and compatibility in composite and insulation materials. Rout (2013) shared that CSP exhibits strong thermal stability and mechanical hardness , making it suitable for pyrolysis and as reinforcement in engineering composite products. Okoya et al. (2020)also demonstrated CSP has strong adsorption ability and durability against chemical compounds, lending itself to sustainable use in various products, including fillers, abrasives, and soil conditioners. These studies confirm CSP's multifunctional, sustainable ability to serve as a soil amendment and a biomaterial for engineering use, E. F. Naeimi *et al.,* and A. Andezai *et al.,*

### *3.2. CHSO Elemental Analysis*

Coconut shell powder (CSP) is an alternative biomass-based natural product with potential applications in agriculture, engineering, and environmental sustainability. An elemental analysis was performed with LECO CS 744 and ONH 836 analyzers at SAIF, IITM, Chennai 600036, and the results were summarized in Table 3.

The carbon levels were between 40.1% and 42.1%, indicating significant organic carbon that imparts hardness and durability. Therefore, CSP is an excellent choice as a natural abrasive in an engineering context, as well as a soil conditioner and slow-release organic amendment in agriculture.

The sulphur levels were low, ranging from 0.0841% to 0.0901%, thereby reducing the risk of soil acidification or potential corrosion on machinery, which could affect agricultural tools and storage systems.

Oxygen levels were 33.3% to 34.7%, and hydrogen levels were 19.6% to 20.2%, confirming that the biomass is primarily of cellulose, hemicellulose, and lignin. When CSP is applied as an organic amendment to agroecosystems, the natural polymers will improve soil porosity, water retention capabilities, and microbial activity, thus enhancing sustainable farming practices.

CSP can also serve as a binder in composting processes, as it improves the cohesion and nutrient retention capability of organic fertilizers. Due to the organic nature of CSP, pre-treatment of some sort may also be needed, and this may include drying or sieving before storage or larger-scale application to reduce clumping to improve flowability for agricultural, industrial, and engineering applications, C. Ngah *et al.,*

Apart from agricultural uses, cash crop straw and residue (CSP) has potential engineering applications serving as a natural abrasive for abrasive jet machining (AJM), reinforcement in composite materials, or biomass-derived fillers for sustainable construction or manufacturing. The environmentally sustainable and biodegradable aspects of CSP make it a cost-effective and environmentally-responsible alternative to synthetic materials, and it is thermally stable, which supports safe usage over extended time frames, C. Ngah *et al., A. A. Okoya et al.,* and A. Andezai *et al.,*

The carbon content for the CSP was in the range of 40.1% to 42.1%, indicating a significant amount of organic carbon, which provides hardness and durability. CSP has high hardness, allowing it to be used effectively as a natural abrasive in abrasive jet machining/polishing/surface finishing applications. Alongside engineering applications, CSP can be used as a soil conditioner, slow-release organic fertilizer, composting additive, or precursor for biochar, all of which can help improve soil fertility and moisture retention.

The biodegradable / biomass-based composition of CSP also makes it suitable for sustainable construction fillers, eco-friendly packaging, and natural reinforcement in composite materials, suggesting a potentially broad functional application across agriculture, industry, and environmental sustainability, C. Liyanage *et al.,* and A. Andezai *et al.,*

The elemental analysis reported here is consistent with earlier studies. For example, Okoya *et al.,* (2020) found that coconut shell char had a carbon content of 60.08% and was confirmed as the most abundant element due to the pyrolytic conversion of organic

**Table 3: CHSO Elemental Composition of Coconut Shell Powder (CSP) (%)**

| S No | Element | Content (%) |
|---|---|---|
| 1 | Carbon (C) | 40.1 – 42.1 |
| 2 | Sulphur (S) | 0.0841 – 0.0901 |
| 2 | Oxygen (O) | 33.3 – 34.7 |
| 4 | Hydrogen (H) | 19.6 – 20.2 |

matter at high temperatures, E. F. Naeim *et al.,* Rout (201) also reported similar elemental patterns when looking at the pyrolysis of coconut shell, where carbon was observed to have a high yield, while hydrogen and oxygen were in low fractions, demonstrating the lignocellulosic characteristics and stability at elevated temperatures, B. Edun *et al.,* Most recently, Fayyadh *et al.,* (2025) reported that coconut shell biochar contained 69.9% carbon, confirming the high carbonization level and the prevalence of an aromatic structure with possible enhanced stability and adsorptive capabilities. The close literature comparability with the elemental data from this analysis suggests that the elemental results from CSP are valid and reliable, thus confirming the potential of CSP as a sustainable and high-carbon biomass resource.

Again, the thermal and elemental characteristics of coconut shell powder confirm it is a versatile, sustainable, and nature-friendly material for agriculture, environmental use, and many engineering fields. The multifunctionality makes it an ideal candidate for practical application and research in sustainable technology.

## CONCLUSION

Coconut Shell Powder (CSP) has been authenticated as a biodegradable, lignocellulosic, and ecologically acceptable substance with major multi-functional abilities. Elements analyzed by CHNSO verify the high contents of carbon (40.1-42.1%), hydrogen (19.6-20.2%), and oxygen (33.3-34.7%), along with little sulfur (0.084-0.090%), confirming it as a biomass origin and environmental suitability. The TGA analysis displays the thermal degradation in three stages, where losses of moisture occurred in the temperature range of 50-150°C (6.097%), losses from thermal degradation of hemicellulose, cellulose and lignin from (156-655°C) resulted in a mass loss of 75.369%, and a final char residue of 18.291% was present at 650°C, which confirms thermal resistance. Because of these properties, CSP has been advantageously applied to agricultural uses, such as soil amendment, slow-release organic fertilizer, and enhanced microbial activity, as well as to engineering applications as natural abrasives, fillers, biochars, and thermal insulating materials. The consistency with the literature supports the conclusion that CSP is a high-carbon sustainable biomass resource. It can be concluded that CSP is a valuable multi-use, green material for sustainable agriculture, industrial uses, and environmental resources.

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## REFERENCES

F. Vieira, H. Santana, M. Jesus, J. Santos, P. P.-Sustainability, and undefined 2024, "Coconut waste: discovering sustainable approaches to advance a circular economy," *mdpi.com*, Accessed: Oct. 05, 2025. [Online]. https://doi.org/10.3390/su16073066

J. V. Mangilal, "DEVELOPMENT OF COCONUT SHELL POWDER-BASED BIOCOMPOSITES FOR PACKAGING OF SELECT DAIRY PRODUCTS," 2021, Accessed: Oct. 05, 2025. [Online]. https://krishikosh.egranth.ac.in/server/api/core/bitstreams/1ced5494-f649-4141-881d-e1c530147965/content

R. Arun, R. Shruthy, R. Preetha, V. S.- Chemosphere, and undefined 2022, "Biodegradable nano composite reinforced with cellulose nano fiber from coconut industry waste for replacing synthetic plastic food packaging," *Elsevier*, Accessed: Oct. 05, 2025. [Online]. https://doi.org/10.1016/j.chemosphere.2021.132786

C. Liyanage, M. P.-P. chemistry, and undefined 2015, "A physico-chemical analysis of coconut shell powder," *Elsevier*, Accessed: Oct. 05, 2025. [Online]. https://doi.org/10.1016/j.proche.2015.12.045

T. Rout, "Pyrolysis of coconut shell," 2013, Accessed: Oct. 05, 2025. [Online]. http://ethesis.nitrkl.ac.in/5346/

C. Ngah, N. Azlisham, … K. A.-I. S. on, and undefined 2014, "Characterization of Coconut (Cocos nucifera L.) Grated Residue by SEM, FTIR, TGA and XRD Analysis," *researchgate.net*, Accessed: Jul. 24, 2025. [Online]. https://www.researchgate.

net/profile/Nor-Ain-Fatihah-Azlisham/publication/305259179_Characterization_of_Coconut_Cocos_nucifera_L_Grated_Residue_by_SEM_FTIR_TGA_and_XRD_Analysis/links/5785f93e08ae3949cf552d0d/Characterization-of-Coconut-Cocos-nucifera-L-Grated-Residue-by-SEM-FTIR-TGA-and-XRD-Analysis.pdf

A. A. Okoya, O. E. Akinola, O. S. Adegbaju, A. B. Akinyele, and O. S. Amuda, "Quantification and Removal of Trichloromethane in Chlorinated Water Using Coconut Shell Activated Carbon," *Ghana Journal of Science*, vol. 61, no. 1, pp. 1–14, Jul. 2020, https://doi.org/10.4314/gjs.v61i1.1

S. N. Fayyadh, N. A. Tahrim, and W. N. A. W. Mokhtar, "Novel eco-friendly methods for producing nanocomposites from celery extract and coconut shell biochar," *International Journal of Environmental Science and Technology*, pp. 1–14, Sep. 2025, https://doi.org/10.1007/s13762-025-06772-z

E. F. Naeimi, K. Selvi, N. U.- Polymers, and undefined 2025, "Exploring the Role of Advanced Composites and Biocomposites in Agricultural Machinery and Equipment: Insights into Design, Performance, and," *mdpi.com*, Accessed: Oct. 05, 2025. [Online]. https://doi.org/10.3390/polym17121691

B. Edun, O. Ajayi, … S. A.-… and B. for, and undefined 2024, "Utilization of Agro-Waste Materials as Viable Strengthening Agents in Carburisation," *ieeexplore.ieee.org*, Accessed: Oct. 05, 2025. https:// doi: 10.1109/SEB4SDG60871.2024.10629809.

A. Andezai, L. Masu, M. M.-I. J. of, and undefined 2020, "Chemical and Morphological Characterization of Coconut Shell Powder, Epoxy Resin and Coconut Shell Powder/Epoxy Resin Composites," *researchgate.net*, Accessed: Jul. 22, 2025. [Online]. https://www.researchgate.net/profile/Andekuba-Andezai/publication/348391037_Chemical_and_Morphological_Characterization_of_Coconut_Shell_Powder_Epoxy_Resin_and_Coconut_Shell_PowderEpoxy_Resin_Composites/links/5ffc6ae745851553a039e1a1/Chemical-and-Morphological-Characterization-of-Coconut-Shell-Powder-Epoxy-Resin-and-Coconut-Shell-PowderEpoxy-Resin-Composites.pdf

"Plant Health, Soil Structure, and Fertility: Developing a Sustainable Future," *researchgate.net*, Accessed: Oct. 05, 2025. [Online]. https://www.researchgate.net/profile/Adel-Ghoneim-3/publication/392893590_Plant_Health_Soil_Structure_and_Fertility_Developing_a_Sustainable_Future/links/6856808acdf1a35eb17484cc/Plant-Health-Soil-Structure-and-Fertility-Developing-a-Sustainable-Future.pdf

K. H. Yeong, T. Liu, L. T. Tan, J. J. Chew, and Y. Wang, "Study of the pyrolysis characteristics and soil amendment potential of palm mesocarp fiber, sago fiber coarse, and sago trunk bark in Malaysia," *Springer*, vol. 25, no. 6, pp. 1854–1869, Jun. 2025, https://doi.org/10.1007/s11368-025-04046-2

A. A. G. Fernando, Manimaran G, and N. S. Ross, "A comprehensive assessment of coconut shell biochar created Al-HMMC under VO lubrication and cooling—challenge towards sustainable manufacturing," *Springer*, vol. 14, no. 8, pp. 9059–9075, Apr. 2024, https://doi.org/10.1007/s13399-022-03164-y

R. K. Rajamony *et al.*, "Eco-friendly approach to thermal energy storage: Assessing the thermal and chemical properties of coconut biochar-enhanced phase change material," *Wiley Online Library*, vol. 6, no. 5, Aug. 2024, https://doi.org/10.1002/est2.679

S. S.-I. P. Journal and undefined 2025, "Investigation of mechanical and water absorption characterization of chitosan and rice bran reinforced biochar-based composites," *Springer*, vol. 34, no. 7, pp. 1029–1038, Jul. 2025, https://doi.org/10.1007/s13726-024-01431-5

S. S.-I. J. of P. A. and and undefined 2024, "Mechanical and water absorption characterization of rice husk and coconut coir reinforced biochar composites," *Taylor & Francis*, vol. 29, no. 6, pp. 398–409, 2024, https://doi.org/10.1080/1023666X.2024.2375254.

C. Fragassa, F. V. de Camargo, C. S.- Sustainability, and undefined 2024, "Sustainable biocomposites: Harnessing the potential of waste seed-based fillers in eco-friendly materials," *mdpi.com*, Accessed: Oct. 06, 2025. [Online]. https://www.mdpi.com/2071-1050/16/4/1526