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Nature Environment & Pollution Technology

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Type of the Paper (Original Research)

Implementation of *Syzygium cumini* Garden Waste Biochar as a sustainable source for the synthesis of paints and pigments

Gaurav R. Hanwatkar[1], Ganesh R. Kale[2], Ratnadip R Joshi[1]†

[1] Department of Chemical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune-411038

[2] Sr. Principal Scientist, CSIR-National Environmental Engineering Research Institute, Nagpur

† Corresponding author: Dr. Ratnadip R Joshi : ratnadip.joshi@mitwpu.edu.in, +91 9423332754,

ORCID ID of Author: 0000-0003-2668-2807

Key Words	Garden waste; Biochar; Pigment; Paint formation; Sustainability; Carbonization
DOI	https://doi.org/10.46488/NEPT.2025.v24i04.B4307 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Hanwatkar, G. R., Kale, G. R. and Joshi, R. R., 2025. Implementation of *Syzygium cumini* garden waste biochar as a sustainable source for the synthesis of paints and pigments. *Nature Environment and Pollution Technology*, 24(4), p. B4307. https://doi.org/10.46488/NEPT.2025.v24i04.B4307

Abstract: With increasing concerns about environmental degradation and the need for sustainable alternatives, the repurposing of organic waste materials such as garden waste biochar is considered a feasible opportunity to mitigate waste accumulation by creating value-added products. The present research study is to identify the potential and investigate the feasibility of utilizing Syzygium cumini garden waste biochar as a sustainable source for pigment and paint formation. The biochar has been produced from garden waste via carbonization, highlighting its chemical composition and physical properties that are conducive to the development of pigment and paint. Furthermore, the paper examines various extraction techniques to isolate pigments from biochar by assessing their colour properties, stability, and compatibility with paint formulations. The findings suggest that Syzygium cumini garden waste biochar holds promise as a sustainable source for pigment and paint formation, offering environmental benefits and contributing to the circular economy. In the case of feed-derived pigment, the Syzygium cumini biochar-based pigment exhibited comparatively better color intensity. Spectrophotometric analysis indicated a high color retention and stability over time, suggesting its viability for various applications in paint and dye industries. This has established the novelty of the work as the commercial pigments are oil based products generating carbon footprints. This research contributes to the growing body of knowledge on sustainable materials utilization and provides insights for the development of eco-friendly paint products in the construction and coatings industries.

1. INTRODUCTION

The Industrial Revolution brought rapid transformation in the socio-economic lives of people on Earth. Due to rampant usage of energy usage, particularly, fossil fuels, the environment is suffering from consequences such as the generation of excessive waste, climate change, soil and water pollution, food shortages, and many more. Emphasizing innovative ways of waste management, the waste can be reduced which mainly contains biomass or biomass-derived products. Many recent epidemics and pandemics have proven that improper waste management poses significant threats to human health. In addition to its unattractive appearance, it leads to air pollution, contaminates water bodies through dumping, and contributes to ozone layer depletion when waste is incinerated, accelerating unwanted climate change. According to the reports, 1.3 billion tons of bio-waste per year has been generated worldwide and it is predicted to increase to 2.2 billion tons per year by 2025 (Nizami et al. 2017). The global market value of biotechnology for bio-waste-to-energy was at around $25.32 billion in 2015 and surged to $40 billion by 2023 (Ubando et al. 2021). Innovative technologies are being researched to convert bio-waste into valuable materials by using techniques like aerobic fermentation, hydrothermal liquefaction, gasification, pyrolysis, carbonization, and anaerobic digestion (Joshi et al. 2023, Reshmy et al. 2022).

Addressing these issues, sustainable development goals have been established, aiming to tackle a range of ecological concerns. One such greener method is to prepare biochar which has multidisciplinary applications including Cement and fertilizer industries, construction industries, composites in polymers, and materials science and engineering (Kinney et al. 2012, Shackley et al. 2012). A carbonaceous substance (carbon neutral/carbon-negative) produced after carbonizing biomass in the absence of oxygen is known as Biochar (Vassilev et al. 2013). Biochar possesses various physiochemical properties depending upon the type of biomass used and the carbonization temperature for the preparation of biochar (Gaur et al. 2024). The carbonization is the promising approach for converting organic material into carbon thermally in the absence of oxygen-rich residue and value-added product. The process of carbonization can accommodate different feedstocks, ranging from municipal solid waste and industrial effluents to agricultural residues and forestry by-products (Joshi et al. 2012, Aruna et al. 2018). In controlled pyrolytic conditions, feedstocks yield a spectrum of carbonaceous materials with tailored properties suited for specific applications. The resultant carbonaceous materials exhibit a myriad of beneficial characteristics including high surface area, chemical stability, electrical conductivity, and mechanical strength, rendering them suitable for various value-added applications (Alam 2013). For instance, biochar derived from biomass carbonization has demonstrated efficacy in soil amendment, water filtration, and carbon sequestration, thereby addressing pressing environmental concerns such as soil degradation and water pollution (Dehankar 2024, Ogwueleka 2009). The bioavailability of heavy metals in soil and water is reduced by the biochar that ultimately reduces the heavy metal pollution improving the quality of contaminated soil and water (Lasaridi et al. 2018, Joshi et al. 2015, Khan et al. 2018).

Biochar, a form of charcoal produced from biomass via pyrolysis or gasification, has gathered attention for its potential as a sustainable alternative to conventional pigments derived from non-renewable sources. Incorporating biochar into paints not only offers a means of utilizing carbonization residues but also reduces the environmental impact of paint production. The utilization of biochar as a pigment in paint is a novel, sustainable concept, and significant research is needed to explore its feasibility, efficacy, and environmental impact. This research aims to address this gap by investigating the properties of biochar as a pigment, its compatibility with different paint formulations, and its potential impact on the performance and sustainability of paint products. The present study focuses on the implementation of Syzygium cumini garden waste biochar for pigment and paint synthesis and explores sustainable alternatives to traditional materials by utilizing organic waste for value-added applications. It investigates biochar properties, and pigment formation mechanisms from feed and offers insights into resource efficiency and environmental benefits in the pigment and paint industry.

2. MATERIALS AND METHODS

2.1 Collection of Garden Waste and Feed Formation

The leafy biomass was collected and it mostly consists of Jamun leaves (Syzygium cumini). The leaves were atmospherically dried for a few days and crushed by using a pulverizer to a particle size of 9-45 mm. The dried leaves were sieved through a 1000μ sieve before feeding in the carbonization process (Toledo 2018, Jain et al. 2022, Awasthi et al 2022, 2021).

2.2 Conversion of Biomass to Biochar

The carbonization reactor configuration is a crucial aspect of the pyrolysis process which involves conversion of biomass into valuable biochar. The reactor's design and setup significantly impact the efficiency and quality of biochar production. During carbonization, biomass undergoes heating within a temperature range of 0- 500 °C, devoid of oxygen but with a continuous flow of nitrogen at a set point of 0.2, over a 4-hour reaction period. Constructed from high-grade stainless steel, the cylindrical chamber ensures durability and withstands high temperatures. A tightly sealed lid creates an oxygen-free environment, preventing biomass combustion. Precision-designed, the lid facilitates easy loading and unloading of biomass, ensuring seamless operation.

The heating system is an integral component of the reactor setup, usually comprised of electric or gas-fired heaters. The temperature control system maintains optimal pyrolysis temperatures, crucial for influencing carbon yield and quality. Temperature control removes volatile components and enhances carbon stability. To improve process efficiency, a syngas collection system captures and redirects evolved gases, including syngas and vapors, for further processing or energy recovery. This maximizes resource utilization and minimizes environmental impact by reducing emissions. The reactor also features an exhaust gas treatment system to mitigate environmental concerns. This system minimizes the release of harmful by-products like tar and particulate matter, ensuring compliance with emissions standards and promoting sustainable biochar production. The overall process of the biochar formation is explained in Figure 1.

2.3 Pigment Preparation from Feed

The pigment formation from dried jamun leaves in a water-based medium involved several key steps as shown in Figure 2. Initially, the dried jamun leaves were collected and finely ground into powder. Following this, a water-based extraction method was employed to extract the pigments. This process entailed immersing the powdered leaves in distilled water for a specific duration to facilitate the extraction of pigments into the solution. After complete soaking, the solution was filtered to eliminate solid debris, resulting in a clear extract enriched with pigments. The filtered solution was then allowed to settle in a normal environment for 24 hours. Subsequently, the settled solution was dried at 50°C in a hot air oven. Once dried, the pigment material was crushed, sieved to ensure uniformity and stored in air-tight containers for further analysis Figure 3.

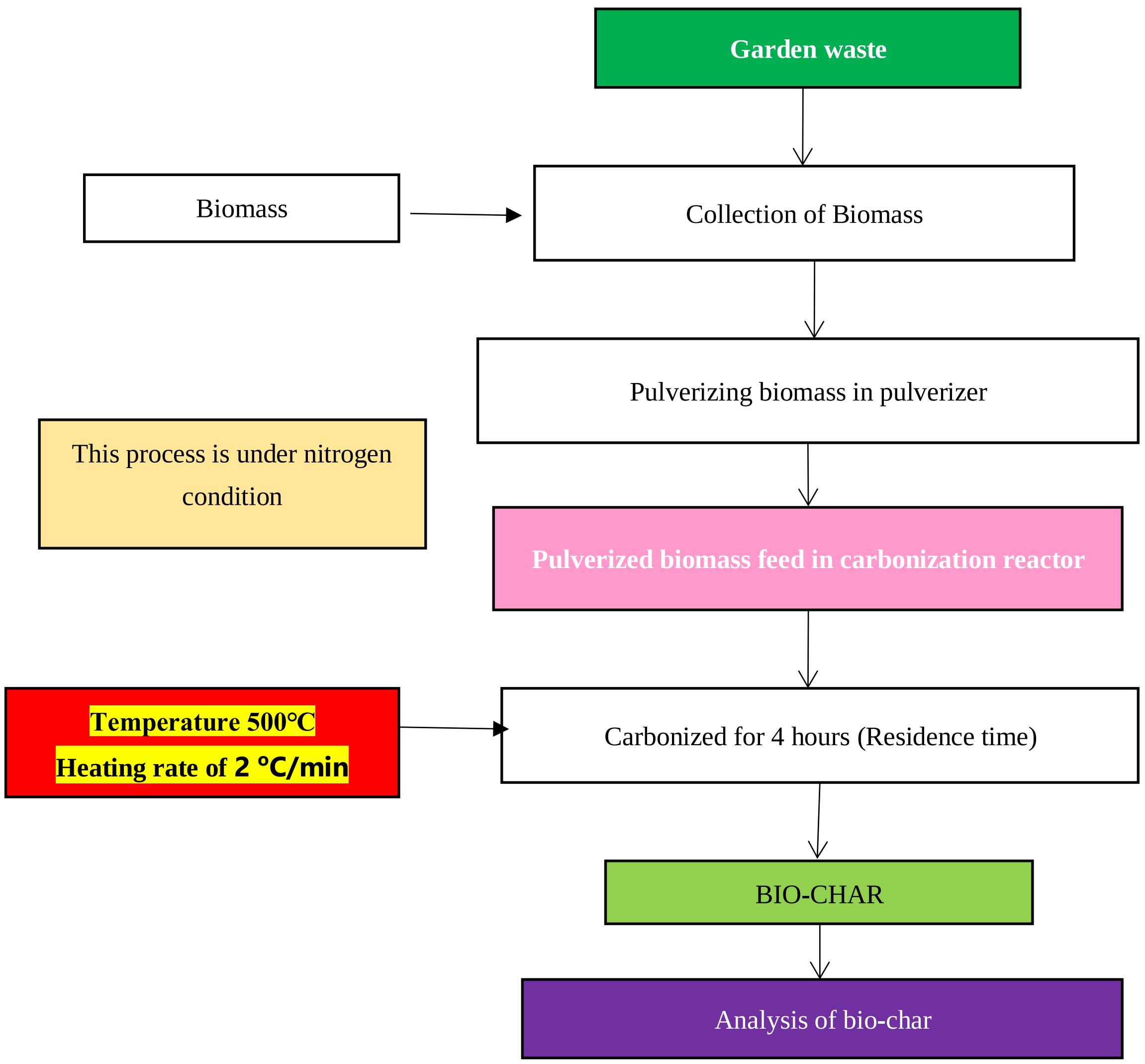


Fig. 1: Block diagram representing carbonization process

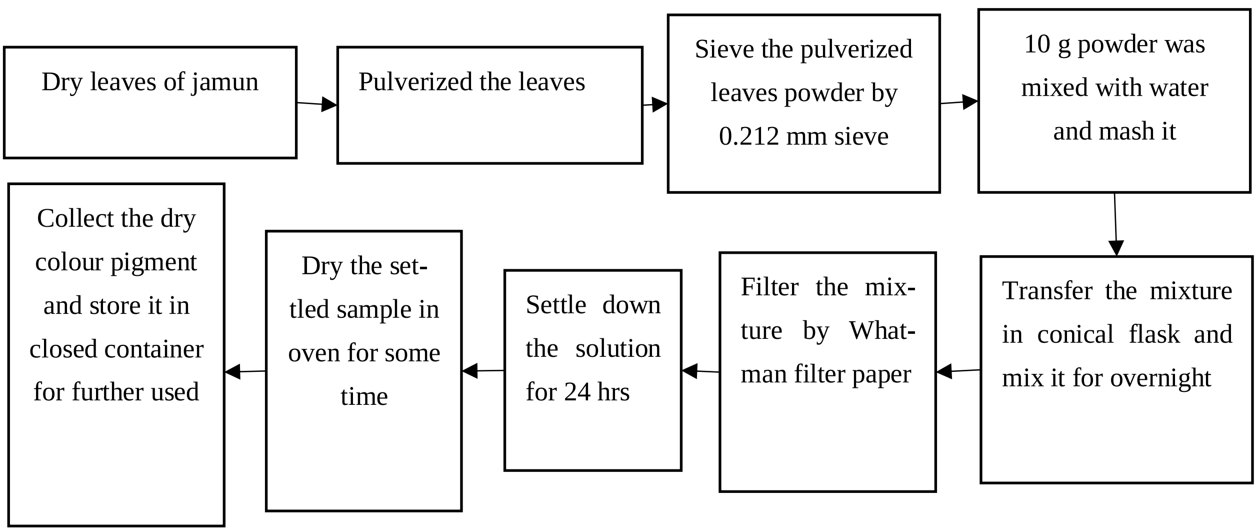


Fig. 2: Block diagram of demonstrating the process of pigment formation from dry leaves

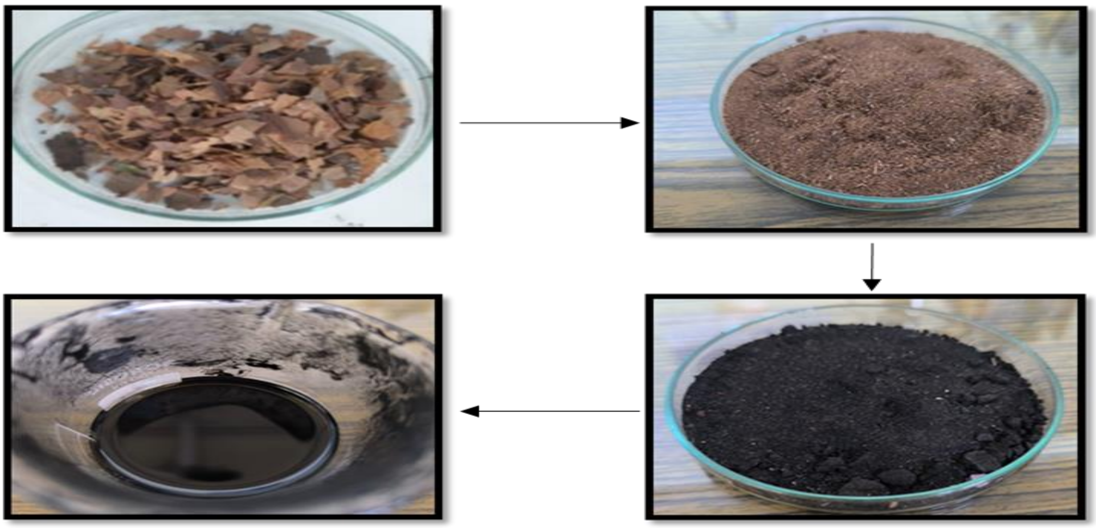


Fig. 3: Process of paint formation using Syzygium cumini garden waste biochar

2.4 Formation of Paint from Extracted Pigment

The biochar has been extracted through carbonization, a process which involves subjecting biomass to high temperatures in a low oxygen environment. 2g sample of biochar was meticulously ground into a fine powder using a mortar and pestle, ensuring uniformity and consistency in particle size. Subsequently, this powdered biochar was sieved through a mesh having a pore size of 0.21 μ. This finely processed bio-char was added into a solution utilized for the thermos-catalytic conversion of polystyrene. This solution was mentioned in detailed research (Hemnea et al. 2023, Reshmy et al. 2022, Angouria et al. 2021, Duan 2020) serves as a crucial component in facilitating the conversion process. The process of the paint was demonstrated in Figure 4 and 5. By integrating the powdered bio-char into this solution, the efficiency and effectiveness of the thermos-catalytic conversion process has been enhanced which potentially unlocks new avenues for sustainable and eco-friendly material transformation (Steiner 2019, Borchard et al. 2018, Jeffery et al. 2011). No chemical modifications are performed for colour stability as results were observed to be quite promising..

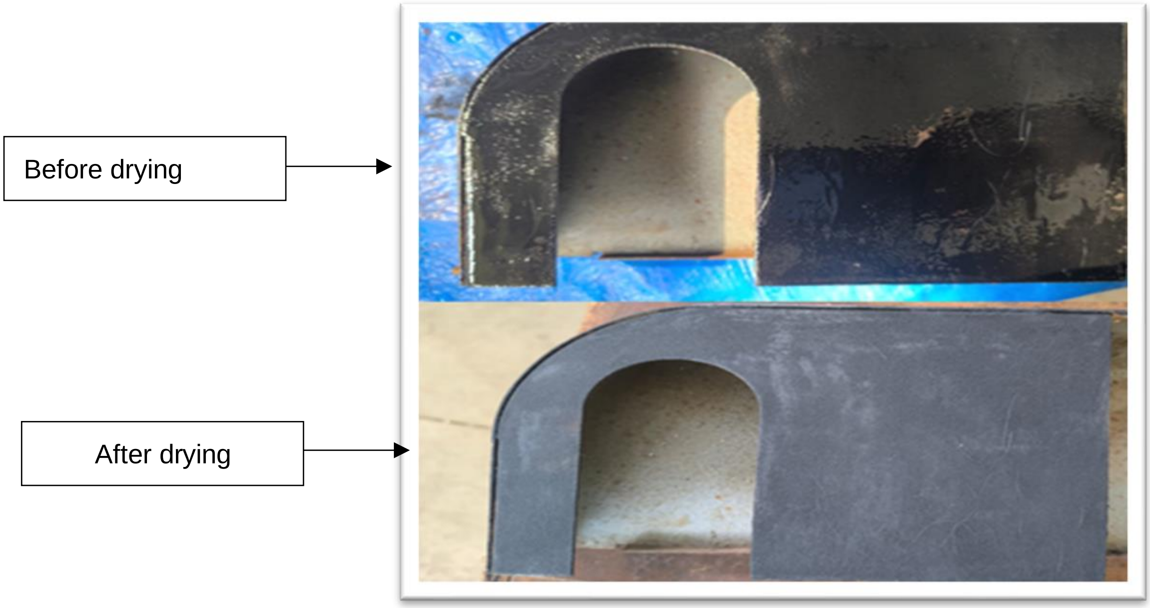


Fig. 4: The pictorial representation of paint before and after drying

Fig. 5: The pictorial representation of water-based feed paint before and after 7 days

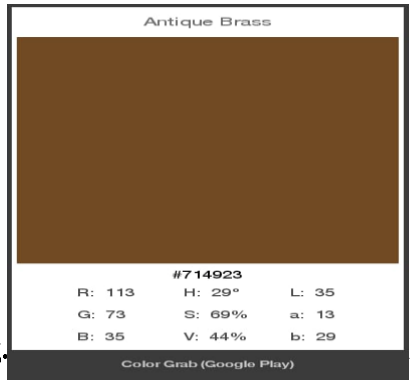
3. RESULTS AND DISCUSSION

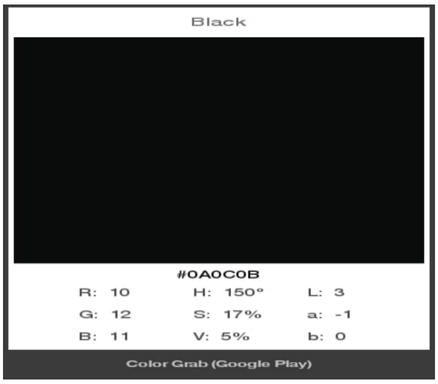
The approximate analysis of biochar is demonstrated in Table 1. After subjecting the material to the carbonization process, the results revealed a moisture content indicates the extent of water present in the sample. The volatile matter suggested the proportion of combustible components that vaporize during heating, reflecting the material's potential for combustion. The ash content indicates the inorganic residue left after complete combustion, influencing the material's purity and suitability for various applications. The pH value indicates the acidity or alkalinity of the material, which can affect its chemical properties and interactions. Additionally, the electrical conductivity (EC) was recorded at V, providing insight into the material's ability to conduct electricity, which can be crucial in certain industrial processes. Finally, the calorific value revealed the highlights of the energy content of the material, essential for assessing its potential as a fuel source. These findings underscore the significance of the carbonization process in altering the composition and properties of the material, elucidating its potential applications in diverse fields.

Table 1: Proximate analysis of samples used for the pigment production

Sl. No.	Sample name	Moisture (%)	Volatile Matter (%)	Ash (%)	Calorific Value (cal/g)	pH	EC
1	Garden waste (jamun leaves feed)	7.65	80	4.45	4163		
2	Garden waste bio-char	-	-	-	5631	8.34	3.66

The experimental results revealed promising outcomes regarding the utilization of Syzygium cumini garden waste bio-char as a sustainable source for pigment and paint formation. In the case of feed-derived pigment, the biochar-based pigment exhibited comparatively better color intensity. Spectrophotometric analysis indicated a high color retention and stability over time, suggesting its viability for various applications in paint and dye industries. Moreover, biochar-derived pigments demonstrated enhanced lightfastness and resistance to environmental degradation compared to conventional alternatives. Furthermore, the incorporation of biochar into paint formulations exhibited favorable rheological properties, contributing to improved paint adhesion and durability Figures 6 and 7. From FTIR analysis it is observed that at wavelengths of 500-1500 cm^{-1}, Aromatic rings and at 2000 cm^{-1}, Carboxylic acids are observed. This validates that the functional groups of biochar are well represented by the samples prepared. The outcomes are very promising and emphasize the potential use of Syzygium cumini garden waste biochar as a sustainable and eco-friendly alternative for pigment and paint production, offering both aesthetic appeal and environmental benefits. The potential of bio-char-derived pigments as sustainable alternatives to conventional pigments, emphasizing their eco-friendly nature and contribution to waste management efforts. Furthermore, it underscores the importance of further research to optimize extraction techniques and refine paint formulations for broader industrial applications.





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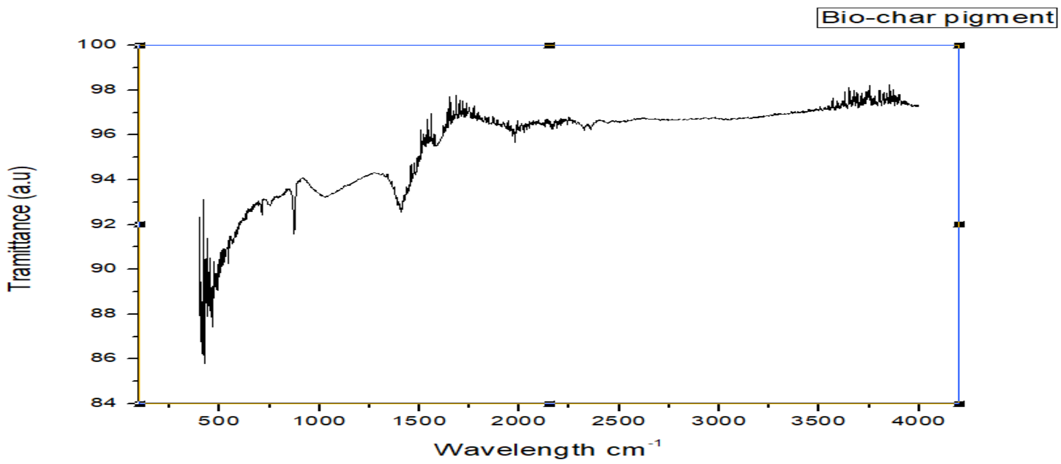

Fig. 7: FTIR analysis confirming the retention and applicability of bio-char pigment

4. CONCLUSIONS

The present research paper explores the potential of generating and deploying Syzygium cumini garden waste biochar as a greener and sustainable source for pigment and paint formation. Through a series of experiments involving the processing of feed and biochar, the study demonstrates the feasibility of extracting pigments from Syzygium cumini garden waste biochar and incorporating them into paint formulations. The biochar-derived pigments exhibit promising color properties suitable for paint production, showcasing its potential as a sustainable alternative to traditional pigments. The novel usage helps in managing waste as well as promotes the development of eco-friendly paint formulations, fostering circular economy and environmental sustainability. Therefore, the utilization of garden waste biochar holds significant promise for the creation of sustainable pigments and paints, offering both environmental and economic benefits.

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