Atlas of Microscopic Images of Biochar—Using Reflected Light Microscopy in Biochar Characterization

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ABSTRACT

Derived through the thermochemical conversion of biomass, biochar is a carbon-rich substance recognized for its significance in environmental applications and sustainable agriculture. As interest in its utilization continues to rise, it becomes crucial to comprehend how the source material and pyrolysis parameters influence the properties of biochar and, consequently, to research the suitability of various analytical methods for characterizing it. Despite the current utilization of numerous physical and chemical methods, the untapped potential of reflected light microscopy warrants further exploration.

While a few recent studies suggest a correlation between certain microscopic characteristics and selected physical and chemical properties of biochar, the data are limited and difficult to compare. This is primarily due to variations in the types of original biomass used and lack of information about pyrolysis conditions. Moreover, because only a limited number of photographs taken under a reflected light microscope are publicly available to-date, it is difficult to evaluate morphological differences between various biochars and other organic materials such as inertinites from coal, charcoal, etc.

To address limited availability of publicly available data, this “Atlas of Microscopic Images of Biochar” presents a collection of more than 300 images contributed by researchers from
Poland, the United States, Canada, Australia, Brazil, and Denmark. These photomicrographs capture optical characteristics of a diverse array of biochar, demonstrating its unique morphological and structural features. This visual documentation can serve as a valuable resource for researchers, industry professionals, educators, and enthusiasts interested in investigating the complexities of biochar forms.

**Keywords**: biochar, biomass, microscopic properties, reflected light microscopy

### ORIGIN AND APPLICATIONS OF BIOCHAR

Biochar is a solid product of biomass pyrolysis, a thermochemical process taking place under a limited supply of oxygen at temperatures above 300 °C. An extensive array of biomass sources, ranging from wood and agricultural crop residues to organic waste, animal manure, and remnants from forestry operations, has been identified and assessed as potential raw materials for biochar production (fig. 1). This diversity of stock material not only contributes to the sustainability of biochar production but also opens up opportunities for a more circular and environmentally conscious approach to biomass conversion (Amin and others, 2016; Weber and Quicker, 2018; Xie and others, 2015b).

Over the past several years, the field of biochar research has experienced remarkable progress, with numerous studies dedicated to refining the properties of biochar for specialized applications. Originally employed primarily as a fertilizer, biochar has evolved into a versatile material, finding applications in water and air filtration systems, waste management, reducing greenhouse gas emissions, treatment of acid mine drainage, soil enhancement, improvement of animal feed, insulation, energy generation, textiles, biocoke applications, and many other innovative uses. The expanding range of biochar applications underscores its growing significance and the ongoing efforts to unlock its full potential across various sectors. The exploration of biochar's capabilities has led to breakthroughs that extend well beyond its initial agricultural application, highlighting its adaptability and utility in addressing a spectrum of environmental and industrial challenges (Amin and others, 2016; Anand and others, 2023; Barber and others, 2018; Bis and others, 2018; Chen and others, 2019; Enaime and others, 2018).

![Figure 1: Photographs showing examples of feedstock materials and their biochars – standard materials from the United Kingdom Biochar Research Centre, photograph courtesy Ondřej Mašek (University of Edinburgh). For scale, the softwood pellets in the upper left corner have a typical diameter of approximately 6 mm.](image-url)
others, 2020; Garcia and others, 2022; Gusti Wibowo, 2019; Igalavithana and others, 2017; Ippolito and others, 2019; Jeguirim and Limousy, 2019; Kalus and others, 2019; Lehmann and Joseph, 2009; Li and others, 2019; Mašek and others, 2018; Mastalerz and others, 2023; Mierzwa-Hersztek and others, 2018; Mood and others, 2022; Panwar and others, 2019; Petersen and others, 2023; Quispe and others, 2022; Rawat and others, 2019; Reddy and others, 2014; Rodriguez-Franco and Page-Dumroese, 2021; Sanei and others, 2024; Schmidt, 2012; Sohi and others, 2010; Wang and others, 2016; Weber and Quicker, 2018; Xie and others, 2015a, 2015b; Yargicoglu and others, 2015).

OPTICAL MICROSCOPY AND BIOCHAR CHARACTERIZATION

Although extensive research has been conducted on the physical and chemical attributes of biomass char, evaluation of their morphological characteristics using optical microscopy remains relatively scarce (Lester and others, 2018; Mastalerz and others, 2023; Petersen and others, 2023). Nonetheless, valuable insights have been drawn from comprehensive microscopic examinations of coal chars (Alvarez and others, 1997; Barranco and others, 2003; Lester and others, 1996), which have led to the development of an optical coal char classification created by the International Committee for Coal and Organic Petrology (fig. 2, Lester and others, 2010).

While coal and biomass undergo similar reaction stages during their conversion from feedstock to char (Avila and others, 2011), variations in their characteristics arise due to differences in the feed material. Examination of various types of biomass and their corresponding chars (including wheat, wheat shorts, miscanthus, olive residue, wood, corn stover, rapeseed, sunflower seed, and distillers dried grain) led to the conclusion that the composition of biomass significantly influences

Figure 2. A petrographic classification system of coal char (modified from Lester and others, 2010).
Figure 3. A petrographic classification system of biomass char (modified from Lester and others, 2018).
the biochar morphology (Lester and others, 2018). For instance, biomass with high lignin content and small particle size produced chars exhibiting a porous structure, while biomass particles with low lignin content and large size produced chars with visible cellular detail. This observation led to the introduction of a biomass char petrographic classification system based on three morphological characteristics: aspect ratio (the ratio of length to width of char fragments), wall thickness, and porosity (fig. 3, Lester and others, 2018).

While the link between biomass characteristics and char morphology has not been rigorously investigated beyond a few studies, a correlation has been established between features obtained through microscopic examination, such as porosity, mineral matter content, or reflectance with physical (such as surface area and density) or chemical (e.g., aromaticity) properties (Mastalerz and others, 2023; Petersen and others, 2023; Sanei and others, 2024). These studies especially suggest that the reflectance of biochar presents a great potential to assess the stability of the biochar in the environment.

Although additional research is needed, the existing data suggest that integrating microscopic analysis in reflected light can be a valuable addition to standard testing parameters to predict biochar quality and stability and to help assess its potential applications (fig. 4). Specifically, microscopic analysis of biochar can help to:

1. provide valuable insights into the micro-morphological characteristics of biochar materials;
2. assess the surface area and porosity of biochar, characteristics that influence biochar’s effectiveness in agricultural and environmental applications;
3. facilitate the observation of impurities and unique micro-features within biochar samples; and
4. evaluate reactivity, and, consequently, stability of biochar in the environment by implementing reflectance measurements.

ATLAS OF BIOCHAR PHOTOMICROGRAPHS IN REFLECTED LIGHT

Because a limited number of images taken under a reflected light microscope is publicly available, this “Atlas of Microscopic Images of Biochar” presents a collection of more than 300 photomicrographs of biochar produced from a wide range of precursory biomass under different pyrolysis conditions. The images were contributed by scientists from the University of Silesia in Katowice (Poland), Indiana University (USA), Geological Survey of Canada, University of Queensland (Australia), United States Geological Survey, TAS-Petrographic Consulting & Auditing and Gerdau Ouro Branco (Brazil), Kentucky University (USA), Geological Survey of Denmark and Greenland, and Aarhus University (Denmark).

The goal of this atlas is to showcase photomicrographs of a broad spectrum of biochar varieties, and consequently capture and document their distinctive structural attributes. The pyrolysis temperature of the biochar samples spans from 300 to 900°C. For comparison, some images of biomass samples that were pyrolyzed to just 200°C have also been included; these samples are accordingly referred to as “heat-altered biomass” as opposed to biochar. The imaged samples were derived from the following feedstock materials (some of which are shown in fig. 4):

- bamboo
- rice hulls (coating of rice grains)
- rice straw
- water hyacinth
- olive tree wood
- pine wood pellet
- pine wood from Colorado
- pine wood from Michigan
- fruit pits
- cedar wood
- locust wood
- miscanthus (silvergrass)
- switchgrass
- willow wood
- unknown hardwood
- demolition wood
- phragmites (wetland grass)
- chicken processing offal (chicken waste from chicken processing plant)
- duckweed (small flowering plant floating on the water)
- sugarcane bagasse
- unknown wood pellets
- eucalyptus wood
- animal manure
- humate (from the Upper Cretaceous Fruitland Formation of Mesaverde Group in New Mexico, USA)
- leonardite (oxidation product of lignite coal from the Fort Union Formation in North Dakota, USA)

It is important to note that the photomicrographs are accompanied by supplementary information. However, while comprehensive details of various properties are available for some images, others furnish only limited information, such as the material source or pyrolysis temperature.
Figure 4. Photographs and photomicrographs of biochar: A and B – unknown hardwood, C and D – rice hull, E and F – Phragmites, G and H – chicken processing offal. A, C, and E show U.S. dimes (17.91 mm diameter) for scale; G shows a U.S. penny (19.05 mm diameter). The scale bar is identical for all photomicrographs.
Where available, the following information provided by the contributors is included:
1. Author(s) of the photo
2. Type of illumination (reflected white light or fluorescent)
3. Objective type (oil immersion or air objective)
4. Biochar source material
5. Additional source material info
6. Temperature of pyrolysis (°C)
7. Residence time at maximum pyrolysis temperature (hours / minutes)
8. Rate of pyrolysis (°C/min)
9. Additional pyrolysis info
10. Average reflectance value of biochar (%)
11. Minimum reflectance value of biochar (%)
12. Maximum reflectance value of biochar (%)
13. Moisture content of biochar (wt %)
14. Ash content of biochar (wt %)
15. Carbon content of biochar (wt %)
16. Sulfur content of biochar (wt %)
17. Volatile matter of biochar (%) 
18. Nitrogen content of biochar (%)
19. Hydrogen content of biochar (%)
20. Oxygen content of biochar (%)
21. Bulk density of biochar (kg/m³)
22. Density of biochar (g/cm³)
23. BET surface area of biochar (m²/g)
24. Additional biochar info (e.g., article link)

The photomicrograph atlas can be accessed via a digital asset management system (IGWS, 2024) hosted by the Indiana Geological and Water Survey at Indiana University, Bloomington, Indiana. The photomicrographs can be searched by the original biomass type and pyrolysis temperature (use the “refine results” button). Metadata for the images contributed by the U.S. Geological Survey are available from Ray and others (2024).

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