



VALORISING CRAB SHELL WASTE INTO FUNCTIONAL BIOCHAR VIA MICROWAVE PYROLYSIS: A GREEN CONVERSION STRATEGY

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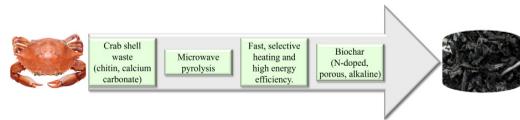
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HIGHLIGHTS

- Crab shell waste is rich in chitin and CaCO₃.
- Microwave pyrolysis offers rapid, selective heating and high-energy efficiency.
- Chitin and CaCO₃/CaO act as intrinsic catalysts for enhanced biochar yield and stability.
- Resulting biochar is N-doped, porous, alkaline and adsorbs heavy metals.
- Key challenges include high capital cost, feedstock variability and need for pilot-scale validation.

GRAPHICAL ABSTRACT



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ABSTRACT

Crab shell waste, a major byproduct of the seafood industry, pose an environmental challenge due to its large volume and slow degradability. However, its richness in chitin and calcium carbonate makes it a promising feedstock for biochar production. Microwave pyrolysis is a green and advanced conversion technology that can efficiently transform crab shell waste into functional biochar. Its rapid and selective heating, combined with the catalytic properties of crab shell components, enhances both the yield and stability of the resulting biochar. This perspective critically reviews the physicochemical properties of crab shells, the mechanisms underlying microwave pyrolysis and the synergistic role of shell-derived catalysts in biochar formation. It highlights microwave pyrolysis as a potentially sustainable approach for marine waste valorisation and advancement of the circular bio-economy.

Potential of Crab Shell Waste

Crab shell waste refers to the discarded exoskeleton of crabs left after the edible meat is removed for consumption or other uses. Improvements in living standards in recent years have driven a growing demand for nutritious and health-conscious food, contributing to the rapid expansion of the seafood industry. Among various seafood options, crab meat is particularly valued for its high nutritional content and desirable taste.

However, an estimated eight million tonnes of crab shell waste are generated globally each year, owing to the fact that only approximately 40% of the crustacean is edible, and the inedible exoskeleton and viscera are routinely discarded (Su *et al.*, 2019). Currently, crab shell waste is typically disposed of in landfills, which poses a significant challenge in regions with limited land availability. Additionally, they are predominantly comprised of chitin, a complex carbohydrate that is slow to degrade (Tsurkan *et al.*, 2021). As a result, crab shell waste can persist in the environment for prolonged periods and improper disposal not only negatively impacts the ecosystem, but also represents a squandering of valuable biomass resources.

Crab shells encompass diverse materials, including chitin, protein, calcium carbonate and trace minerals like iron, zinc, phosphorus and copper (Azelee *et al.*, 2023). The chitin component constitutes approximately 15% to 40% of the dry weight of crab shells, while calcium carbonate (CaCO₃) makes up about 20% to 50%, depending on species and age of the crab (Su *et al.*, 2019). Chitin is a nitrogenous biopolymer composed of N-acetylglucosamine monomers connected by β -1,4-glycosidic bonds (Liu *et al.*, 2023). As crab shells undergo pyrolysis, the embedded chitin breaks down into nitrogenous volatiles, notably ammonia, pyrroles and pyridines (Zeng *et al.*, 2015). Ammonia can be employed as a fertiliser, and

pyridines can serve as precursor materials for the production of pharmaceuticals, agrochemicals and other chemicals. The catalytic nature of chitin supports the breakdown of biomass during pyrolysis, thereby improving the efficiency of conversion and influencing the composition of end products (Wang & Shen, 2022). This is attributed to the extensive surface area of chitin, providing numerous active sites for the pyrolysis reaction (Tsiptsias *et al.*, 2009).

The crab shell waste also contains calcium carbonate, which functions as a catalyst in the pyrolysis reaction (Araújo *et al.*, 2020). The high surface area and porosity of the catalyst enhance its ability to adsorb organic compounds, facilitating their thermal breakdown and improving the overall efficiency of the pyrolysis process (Liu *et al.*, 2015). Moreover, at elevated temperatures of around 700°C, CaCO₃ undergoes transformation into Calcium oxide (CaO), which acts as an active catalyst by releasing carbon dioxide (CO₂) (Ishimura *et al.*, 2021). CaO is a crystalline structure comprising calcium (Ca²⁺) and oxygen (O²⁻) ions (Li *et al.*, 2021). Due to the slight electronegativity of Ca²⁺ as an alkaline earth metal, its Lewis acidity is limited. Meanwhile, the corresponding oxygen ion is strongly basic. Consequently, CaO exhibits alkaline properties, providing alkaline sites that facilitate acid-base catalytic reactions. In addition to improving pyrolysis performance, calcium carbonate plays a crucial role in reinforcing the stability of the produced biochar. It has been reported that the improved biochar stability arises from the interaction of calcium carbonate-derived nitrogenous groups with organic carbon, forming stable pyridine-N structures through dimerisation and cyclisation (Nan *et al.*, 2020). Thus, crab shell waste is potentially suitable for use as a pyrolysis feedstock, thereby realising waste recycling and conversion into value-added products such as biochar.

This perspective explores the application of microwave pyrolysis for valorising crab shell waste, with a focus on recent advancements in biochar production. Highlighting the potential of this emerging approach contributes to shaping sustainable and innovative waste valorisation solutions.

Microwave Pyrolysis

As an emerging thermochemical approach, microwave pyrolysis employs microwave radiation to achieve fast and targeted heating, making it particularly suitable for processing carbon-based feedstocks (Dubey & Dube, 2024). During microwave heating, the applied energy induces over one million dipole rotations per second at the atomic scale (Sharif *et al.*, 2018). This rapid molecular motion generates frictional heat within the material, allowing it to quickly reach the desired high temperature (Yin, 2012). Pyrolysis is an efficient method for converting organic waste into value-added products by heating in the absence of oxygen, resulting in the formation of biochar, bio-oil and syngas. Notably, microwave pyrolysis can be carried out in a closed system, which minimises environmental pollution and enhances operational safety (Lam *et al.*, 2016).

Biochar has emerged as a promising material in wastewater treatment applications due to its excellent adsorption capacity for a wide range of pollutants (Jagadeesh & Sundaram, 2023). The effectiveness of biochar as an adsorbent is primarily attributed to its porous structure and high surface area, which provide abundant active sites for capturing a wide range of wastewater contaminants, including heavy metals, organic compounds and excess nutrients (Manyuchi *et al.*, 2018; Chen *et al.*, 2019; Sarkar *et al.*, 2024). Additionally, wastewater treated with biochar can be repurposed for non-potable uses such as irrigation, thereby fulfilling the objective of wastewater reuse (Quispe *et al.*, 2022). Notably, biochar exhibits long-term stability, reducing

the necessity for frequent replacement (Wang *et al.*, 2021). These properties make biochar an attractive option for wastewater treatment, offering a cost-effective and environmentally sustainable solution.

Biochar Derived from Crab Shell Waste

Crab shell biochar exhibits a complex and multifunctional composition, combining carbonaceous matrices with mineral-rich inorganic phases; these are the features inherited from the unique biochemical architecture of crustacean exoskeletons (Faizal *et al.*, 2024). The organic fraction of crab shells is predominantly composed of chitin, a nitrogen-containing biopolymer, which undergoes partial carbonisation during pyrolysis to form nitrogen-doped carbon structures with enhanced surface reactivity (Foong *et al.*, 2024). Simultaneously, residual proteins and lipids contribute to the generation of volatile compounds and tars, which facilitate the development of micro- and mesoporous structures within the biochar matrix (Leng *et al.*, 2021). The volatilisation of these thermally labile organics also promotes the formation of oxygen-containing surface functional groups (such as hydroxyl, carboxyl and carbonyl groups) known to modulate the biochar's hydrophilicity and adsorption affinity (Chen *et al.*, 2024).

In addition, the inorganic constituents, mainly composed of CaCO_3 and other mineral species, render the resulting biochar calcium-rich and strongly alkaline, which is particularly advantageous for the remediation of acidic contaminants (Pattanaik *et al.*, 2025). The coexistence of a porous carbon network, alkaline mineral phases and a functionalised surface endows crab shell biochar with a highly heterogeneous and reactive structure, underpinning its effectiveness in a wide range of environmental applications. Crab shell biochar can be used for pH adjustment (Ratnasari *et al.*, 2021; Hopkins *et al.*, 2022) and removal of

heavy metals like cadmium (Cd) in wastewater up to a quantity of 73.5 mg/g (Lin *et al.*, 2023).

Challenges

While biochar presents numerous benefits, there are some challenges to consider. Scalability is a primary concern, as large-scale production and application of biochar must be economically viable and technically feasible. Microwave pyrolysis offers the potential of increase efficiency and better control of the whole pyrolysis process. As technology continues to advance, improvements in microwave system design and optimisation of process parameters can improve the overall effectiveness of the method. However, the implementation of a microwave pyrolysis system may require a significant initial investment in specialised equipment. The high investment required for establishing and sustaining microwave pyrolysis infrastructure limits its feasibility for broad industrial deployment. Furthermore, because biomass feedstocks are heterogeneous, the efficiency of microwave pyrolysis may be affected by these changes. Adapting technology to handle different feedstocks is also a challenge. Considering the economic feasibility and convenience, microwave pyrolysis technology is superior to the existing technology (conventional pyrolysis) in terms of efficiency, cost-effectiveness and product quality.

Conclusions

This perspective critically evaluates the viability of utilising crab shell waste as a renewable resource for biochar production through microwave pyrolysis. It highlights a promising thermochemical pathway for marine waste valorisation by converting slow-degradable crustacean waste into high-value carbon materials through a green and efficient process. However, current findings are largely limited to lab-scale studies, and further pilot-scale assessments are needed to evaluate its

scalability. Future research should focus on optimising process parameters and thoroughly characterising the resulting biochar to enable its application in targeted environmental remediation and resource recovery efforts.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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