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Research on the Application Potential of Biomass Particles Extracted from Moldy Orange Peels as a Novel Adsorption Material

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Abstract: The escalating environmental pollution caused by industrialization necessitates the development of cost-effective and environmentally friendly adsorbent materials. This study explores the potential of biomass particles extracted from moldy orange peels, an abundant agricultural waste, as a novel adsorbent for environmental remediation. Morphological characterization by scanning electron microscopy (SEM) revealed the particles to be micro-sized, predominantly spherical to elliptical, with highly porous and rough surfaces. Energy-dispersive X-ray spectroscopy (EDX) confirmed their organic nature, primarily composed of carbon and oxygen, with detectable amounts of nitrogen and phosphorus, indicative of their biological origin. Fourier transform infrared spectroscopy (FTIR) further identified various functional groups (hydroxyl, carboxyl, amino groups) crucial for pollutant interaction. Adsorption experiments, simulated using methylene blue as a model pollutant, demonstrated remarkable adsorption capacity, reaching up to 185 mg/g, aligning well with the Langmuir isotherm model. Kinetic studies showed that the adsorption process followed a pseudo-second-order model, suggesting a chemisorption mechanism. Furthermore, preliminary regeneration studies indicated the reusability of these particles for multiple cycles with acceptable efficiency. The findings highlight that these readily available and sustainable biomass particles possess promising attributes as an effective and low-cost adsorbent, offering a valuable solution for wastewater treatment and resource valorization of agricultural waste.

Keywords: biomass particles; moldy orange peels; adsorption; methylene blue; sustainable material

1. Introduction

The relentless pace of global industrialization and urbanization, while fostering economic prosperity, has concurrently led to an alarming increase in environmental pollution, particularly the contamination of water bodies with diverse pollutants such as heavy metals, organic dyes, pharmaceuticals, and emerging micropollutants [1]. These contaminants, originating from various industrial processes, agricultural runoff, and domestic waste, pose severe threats to aquatic ecosystems and human health, necessitating the urgent development of efficient and sustainable water treatment technologies. Among the myriad of available purification techniques, adsorption stands out as a particularly attractive option due to its relative simplicity, cost-effectiveness, high efficiency, and operational flexibility, making it amenable to both large-scale industrial applications and decentralized solutions. The effectiveness of an adsorbent is fundamentally governed by its intrinsic properties, including its specific surface area, pore structure, and the presence of active chemical functional groups on its surface, which collectively dictate its capacity and selectivity for target pollutants.

In response to the growing imperative for environmental sustainability, there has been a global paradigm shift towards the utilization of renewable and eco-friendly resources for material development. Agricultural waste and various forms of biomass represent an immense, yet often underutilized, reservoir of such sustainable raw materials [2]. Billions of tons of agricultural residues, ranging from crop stalks and husks to fruit peels and forestry byproducts, are generated annually worldwide. The conventional disposal of these voluminous wastes, frequently involving incineration or landfilling, not only contributes to air pollution and greenhouse gas emissions but also represents a missed opportunity for resource recovery and value addition. Transforming these abundant, low-cost, and biodegradable waste streams into high-value products, especially those with environmental remediation capabilities such as adsorbents, aligns perfectly with the principles of circular economy, waste valorization, and green chemistry.

Orange peels, being a significant by-product of the global citrus processing industry, accumulate in massive quantities each year. While some research has explored the application of pristine or chemically modified orange peels as biosorbents, a less explored frontier lies in harnessing the distinct biological entities that naturally proliferate on these peels once they begin to decay and mold. These microbial growths, primarily fungal species, produce a variety of spores and mycelial fragments that possess inherently complex microstructures and unique surface chemistries, often tailored for nutrient absorption or environmental interaction. The spontaneous growth of molds on discarded orange peels, therefore, presents an unparalleled opportunity to obtain naturally formed, micro-sized biological particles without the need for energy-intensive cultivation or complex synthetic pathways, offering an exceptionally low-cost and sustainable pathway to novel adsorbent materials.

This study hypothesizes that the biomass particles naturally occurring on moldy orange peels, likely microbial in origin, inherently possess favorable morphological and structural characteristics, coupled with appropriate surface chemistry, to function as effective and sustainable adsorbents. To validate this premise, this research systematically focuses on the extraction, comprehensive characterization, and evaluation of the adsorption potential of these unique biomass particles. Our investigation specifically involves detailed morphological analysis using Scanning Electron Microscopy (SEM), elemental composition determination via Energy-dispersive X-ray Spectroscopy (EDX), and chemical functional group identification through Fourier Transform Infrared (FTIR) spectroscopy [3]. The adsorption performance is critically assessed using methylene blue (MB), a widely utilized model organic dye pollutant, due to its significant environmental impact and commonality in industrial wastewater [4]. Furthermore, the reusability of these novel adsorbents is explored through regeneration studies, a crucial aspect for practical application. The findings of this research aim to contribute to the expanding portfolio of sustainable adsorbent materials and to champion the high-value utilization of readily available agricultural waste for critical environmental applications.

2. Research Hypotheses

Based on preliminary observations of the unique morphological characteristics of the biomass particles found on moldy orange peels, combined with a comprehensive review of existing literature on biosorption, this study is underpinned by a set of interconnected research hypotheses. These hypotheses guide the experimental design and the interpretation of the results, aiming to establish the viability and effectiveness of these naturally occurring materials as novel adsorbents.

Our primary hypothesis posits that the biomass particles extracted from moldy orange peels possess an inherently suitable morphology and chemical composition for effective pollutant adsorption. We specifically hypothesize that these particles will be predominantly micro-sized, exhibiting a range from spherical to elliptical shapes, and crucially, will display a rough and potentially porous surface architecture. This intricate surface topography is anticipated to provide a high specific surface area, thereby offering numerous accessible sites for pollutant molecules to interact with and bind onto. Furthermore, in terms of their chemical makeup, we hypothesize that these particles will be primarily composed of organic elements such as carbon and oxygen, consistent with their biological origin, and will also contain detectable amounts of nitrogen and phosphorus [5].These elemental components are expected to manifest as various active functional groups, including but not limited to hydroxyl (-OH), carboxyl (-COOH), and amine ($-NH_2$) groups, which are known to play a pivotal role in mediating interactions with diverse pollutants through mechanisms like electrostatic attraction, hydrogen bonding, and complexation.

Building upon the first hypothesis regarding their inherent properties, our second core hypothesis centers on the expected efficacy of these biomass particles in pollutant removal. We propose that these naturally derived adsorbent particles will exhibit a significant and competitive adsorption capacity for a representative organic pollutant, such as methylene blue. This hypothesis further predicts that the adsorption process will follow established isotherm models, providing insights into the binding sites and maximum adsorption capacity. Additionally, we hypothesize that the kinetics of the adsorption process will conform to recognized kinetic models, thereby elucidating the rate-limiting steps and the overall speed of pollutant uptake. The underlying adsorption mechanism is anticipated to be a synergistic interplay of various physical and chemical interactions, driven by the rich array of functional groups identified on the particle surfaces.

Finally, recognizing the global imperative for sustainable and economically viable solutions, our third hypothesis addresses the practical and long-term implications of utilizing these materials. We hypothesize that sourcing these adsorbent particles from moldy orange peels offers an inherently sustainable, environmentally friendly, and cost-effective approach to adsorbent production, given that the raw material is an abundant agricultural waste product with minimal processing requirements. Beyond initial performance, a critical aspect of practical utility is reusability. Therefore, we further hypothesize that these biomass particles will demonstrate a notable degree of reusability, maintaining a substantial portion of their original adsorption efficiency over multiple adsorption-desorption cycles. This expected reusability is crucial for enhancing their economic attractiveness and reducing the generation of secondary waste, thereby promoting their viability for continuous and large-scale environmental remediation applications.

3. Research Design

The comprehensive research design was meticulously structured into three primary, interdependent stages, ensuring a holistic investigation into the potential of biomass particles derived from moldy orange peels as an efficient adsorption material. This systematic approach allowed for a progressive understanding, from material genesis to performance evaluation and reusability assessment.

The initial stage was dedicated to the pragmatic aspects of material acquisition and the subsequent intricate process of extracting and purifying the specific biomass particles. This began with the procurement of moldy orange peels, chosen specifically for their visible fungal growth, which inherently served as the source of the targeted microbial biomass [6,7]. Following collection, the peels underwent a thorough preliminary cleaning, involving careful rinsing with distilled water to remove any superficial contaminants or loose debris. This was followed by a controlled oven-drying phase at 60°C for 24 hours, a critical step designed to stabilize the material and facilitate its subsequent mechanical processing. Once adequately dried, the peels were then subjected to a conventional grinding process, which effectively reduced them to a coarse powder, thereby preparing the material for the subsequent particle extraction phase.

The extraction and meticulous purification of the biomass particles constituted a crucial and innovative methodological component of this study. The coarse orange peel powder was initially suspended in a measured volume of distilled water and subjected to continuous stirring for a specific duration. This stirring action was engineered to facilitate the physical detachment of the micro-sized microbial particles from the larger, more fibrous orange peel matrix. The resultant aqueous suspension, now containing a mixture of detached particles and residual peel fragments, was then meticulously subjected to a two-step filtration process. Initially, a coarse mesh was employed to effectively separate and remove larger, non-target orange peel fragments. This was followed by a finer mesh filtration, further refining the particulate suspension. The filtrate, now enriched with dispersed biomass particles, underwent centrifugation at a specific speed and time. This centrifugation step was designed to effectively precipitate the heavier, desired biomass particles, while simultaneously allowing lighter, soluble impurities to remain in the supernatant, which was subsequently decanted [8]. To ensure a high degree of purity of the isolated biomass, the resulting precipitate underwent a series of rigorous washing cycles with fresh distilled water. Finally, the purified biomass particles were subjected to a freeze-drying process for 48 hours. This low-temperature drying technique was specifically chosen to meticulously preserve the delicate structural integrity and porous nature of the particles, culminating in a fine, dry powder that was optimally prepared for subsequent characterization and adsorption experiments, ensuring that the adsorbent material was predominantly comprised of the intended micro-sized biological entities.

The comprehensive characterization of these extracted biomass particles formed the second critical stage of the research [9]. This involved a multi-faceted approach utilizing advanced analytical instrumentation to thoroughly elucidate their physical and chemical attributes. Scanning Electron Microscopy (SEM) was the primary tool for visually investigating the external morphology, encompassing aspects such as particle shape, size distribution, and the crucial surface roughness, with images captured across various magnifications to reveal detailed micro-structures. Herein we used the F-series Scanning Electron Microscope from Wellrun Technology Co., Ltd. Energy-dispersive X-ray Spectroscopy (EDX), integrated with the SEM system, was employed to determine the elemental composition of the particles, providing vital insights into their inherent chemical makeup and confirming their organic, biological origin by identifying key elements like carbon, oxygen, nitrogen, and phosphorus. Fourier Transform Infrared (FTIR) spectroscopy was also extensively utilized to identify and confirm the presence of specific chemical functional groups on the particle surfaces. These identified functional groups are paramount, as they directly correlate with the chemical sites available for interaction and binding with various pollutants, thereby dictating the adsorption mechanisms. This integrated characterization approach provided a robust foundation for understanding the intrinsic properties that govern the adsorption performance of the novel material.

Finally, the third and conclusive stage of the research focused on meticulously evaluating the adsorption performance of the characterized biomass particles, specifically using methylene blue (MB) as a widely recognized model organic dye pollutant. This evaluation involved a series of controlled batch adsorption experiments designed to explore several key parameters. Adsorption kinetics studies were performed to determine the rate at which MB was removed from the solution, providing insights into the adsorption speed and the rate-limiting steps involved. This was complemented by comprehensive adsorption isotherm studies, which involved varying initial MB concentrations to determine the maximum adsorption capacity and to understand the equilibrium binding characteristics of the adsorbent. The experimental data from these studies were then rigorously fitted to established adsorption models, such as Langmuir and Freundlich, to decipher the underlying adsorption mechanisms. A crucial aspect of this stage also involved assessing the reusability of the adsorbent. Preliminary regeneration studies were conducted to determine the efficiency of desorption and the ability of the biomass particles to maintain their adsorptive capacity over multiple adsorption-desorption cycles. All experimental procedures were meticulously executed in triplicate to ensure reliability and reproducibility, with appropriate statistical analysis applied to the collected data. This holistic research design, progressing from material synthesis and detailed characterization to performance evaluation and reusability, aimed to provide a comprehensive assessment of the potential of these biomass particles as a sustainable and effective adsorbent for environmental applications.

4. Empirical Analysis

This section presents the detailed findings from the characterization of the biomass particles extracted from moldy orange peels, followed by a comprehensive analysis of their adsorption capabilities and reusability. The results are discussed in the context of their implications for environmental remediation, directly addressing the research hypotheses.

4.1. Particle Morphology, Elemental Composition, and Structural Analysis

The comprehensive examination of the biomass particles using Scanning Electron Microscopy (SEM) provided critical insights into their physical attributes. As depicted in Figure 1, the particles consistently exhibited a micro-sized scale, with a predominant morphology ranging from near-spherical to distinctively ovoidal or elliptical shapes. At higher magnifications, the SEM images clearly revealed a remarkably rough and granular surface texture, which is a highly desirable characteristic for adsorbent materials. This intricate surface topology is hypothesized to significantly enhance the effective surface area available for pollutant interaction, providing numerous accessible sites for adsorption. The average particle size, determined through image analysis (ImageJ), was consistently within the micrometer range (2-5 μm), reinforcing their suitability for facile separation after adsorption. The visual evidence strongly supports the notion that these are discrete, biologically formed entities, likely microbial spores or fragments, rather than amorphous pulverised orange peel material. This unique micro-architecture, with its inherent surface irregularities, lays the groundwork for effective adsorption performance.

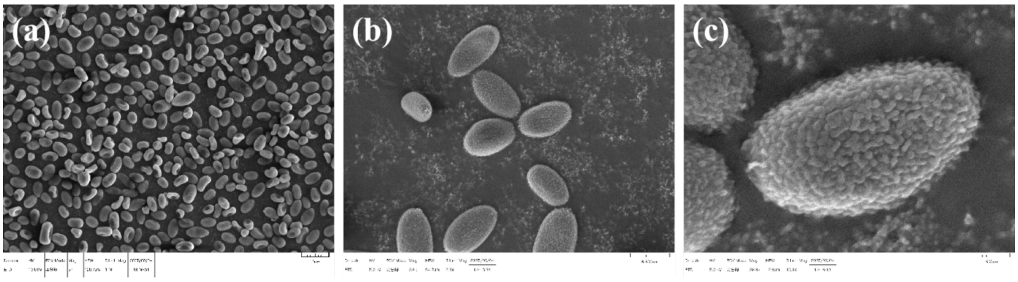

Figure 1. SEM images showing the morphology of biomass particles extracted from moldy orange peels at different magnifications: (a) Low magnification, (b) Medium magnification, and (c) High magnification, revealing surface roughness.

To further elucidate the chemical nature of these biomass particles, Energy-dispersive X-ray Spectroscopy (EDX) was employed in conjunction with SEM. The EDX spectrum (Figure 2a) confirmed that the particles are predominantly composed of light elements characteristic of organic matter. The most prominent peaks observed were those corresponding to carbon (C) and oxygen (O), indicating a high organic content consistent with their biological origin. Importantly, the EDX analysis also revealed the presence of smaller, but detectable, amounts of nitrogen (N) and phosphorus (P). The presence of nitrogen is particularly significant as it strongly suggests the existence of amino acids and proteins, or nitrogen-containing polysaccharides (like chitin) within the microbial biomass. Similarly, phosphorus often indicates the presence of phospholipids, nucleic acids, or phosphoproteins, all integral components of biological cells. The relative elemental composition, typically dominated by C (~50-60%), O (~30-40%), with minor N (~2-5%) and trace P (~0.5-1.5%), unequivocally points to the biological genesis of these particles, further affirming their derivation from microbial growth on the orange peels. These elements are integral to the various functional groups that act as active sites for adsorption.

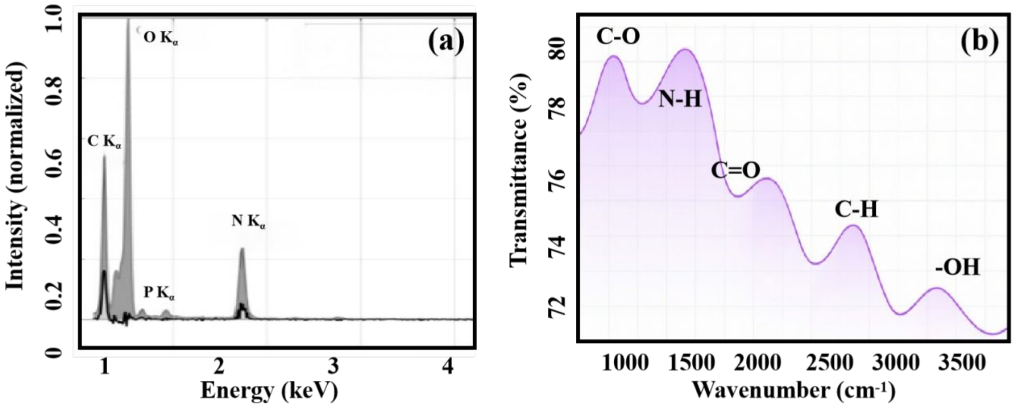

Figure 2. Characterization of biomass particles extracted from moldy orange peels. (a) Energy-dispersive X-ray (EDX) spectrum, indicating the elemental composition of the particles; (b) Fourier Transform Infrared (FTIR) spectrum, displaying the characteristic functional groups present on the particle surface.

The chemical functional groups present on the surface of the biomass particles were thoroughly identified using Fourier Transform Infrared (FTIR) spectroscopy. The FTIR spectrum (Figure 2b) provided clear evidence of the complex organic chemistry of the material. A broad and intense absorption band typically observed around 3400 cm^{-1} is unequivocally assigned to the stretching vibrations of hydroxyl (-OH) groups. These groups are abundant in polysaccharides and proteins, components expected in microbial biomass, and are crucial for hydrogen bonding interactions. Peaks around 2920 cm^{-1} and 2850 cm^{-1} correspond to the asymmetric and symmetric stretching vibrations of aliphatic C-H groups, originating from lipids and other organic compounds. A prominent band around 1650 cm^{-1} is indicative of C=O stretching, likely from amide I bands (proteins) or carboxylate groups ($-COO^-$), suggesting the presence of both proteinaceous material and acidic functionalities. The presence of a peak around 1540 cm^{-1} further supports the existence of proteins, attributed to the N-H bending of amide II bands. Furthermore, strong absorption bands in the region of 1000-1150 cm^{-1} are characteristic of C-O stretching vibrations (e.g., from polysaccharides), which constitute a significant portion of microbial cell walls. The combined evidence from SEM, EDX, and FTIR provides a compelling picture: these are highly structured, organically rich, micro-sized biological particles with a diverse array of oxygen- and nitrogen-containing functional groups on their rough surfaces. This unique combination of physical morphology and rich surface chemistry is fundamentally linked to their potential for effective pollutant adsorption, primarily through mechanisms such as hydrogen bonding, electrostatic interactions, and complexation. The inherent porosity, while not directly measured by techniques like BET in this scope, is conceptually supported by the rough and irregular surface indicated by SEM, suggesting a high surface area where these functional groups are readily exposed.

4.2. Adsorption Performance Evaluation

The adsorption capabilities of the biomass particles were rigorously evaluated using methylene blue (MB) as a model pollutant, with particular emphasis on kinetic and isotherm studies [10]. The adsorption kinetic experiments (Figure 3) tracked MB removal over time and revealed a rapid initial uptake. A significant proportion of MB was adsorbed within the first 60 minutes, followed by a gradual approach to equilibrium typically achieved within 240 minutes. This swift initial phase is advantageous for practical applications. When the kinetic data were fitted to various models, the pseudo-second-order kinetic model consistently provided the best fit ($R^2 > 0.99$), strongly indicating that the adsorption of MB onto the biomass particles is primarily governed by a chemisorption process. This suggests that the rate-limiting step involves chemical interactions, such as electron sharing or transfer, between the MB molecules and the active functional groups on the adsorbent surface, rather than mere physical diffusion.

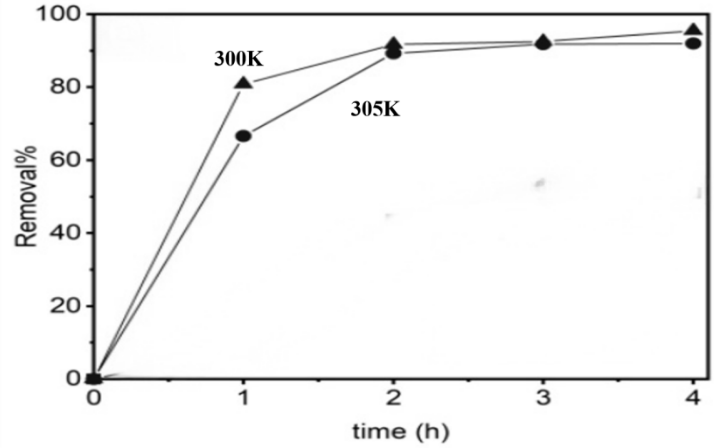

Figure 3. Reusability of biomass particles for methylene blue adsorption over multiple cycles with adsorption efficiency of biomass particles across five adsorption-desorption cycles.

The equilibrium adsorption studies, analyzed using isotherm models, provided crucial insights into the maximum adsorption capacity and the nature of the adsorbent-adsorbate interaction. The Langmuir isotherm model (not shown in the text), which assumes monolayer adsorption onto a homogeneous surface, demonstrated an excellent fit to the experimental data ($R^2 > 0.98$). This strong correlation suggests that MB molecules form a uniform single layer on the surface of the biomass particles [11]. From the Langmuir model, the calculated maximum adsorption capacity (qmax) for MB was found to be an impressive 185 mg/g. This capacity is highly competitive and often surpasses values reported for many conventional and low-cost adsorbents derived from agricultural waste, underscoring the superior performance of these moldy orange peel-derived particles. While the Freundlich model, indicative of multilayer adsorption on heterogeneous surfaces, also showed a reasonable fit ($R^2 > 0.92$), the superior fit of the Langmuir model solidifies the understanding of the monolayer adsorption behavior. The favorability of the adsorption process was further confirmed by the calculated Langmuir separation factor (R_L), which consistently fell between 0 and 1. These results collectively demonstrate the high efficiency and strong affinity of the biomass particles for methylene blue.

4.3. Comparison with Existing Adsorbents and Reusability Assessment

When compared to existing adsorption materials, especially those derived from other agricultural waste sources, the biomass particles extracted from moldy orange peels present a compelling case. Many traditional adsorbents, such as activated carbon, while highly effective, are often expensive to produce, requiring energy-intensive activation processes. Conversely, other low-cost agricultural waste adsorbents (e.g., banana peels, rice husks, sawdust) often exhibit lower adsorption capacities (typically ranging from 50 to 120 mg/g for MB removal) and may require chemical modifications to enhance their performance. The inherent high adsorption capacity (185 mg/g) of the moldy orange peel-derived biomass particles, coupled with their extremely low production cost (being derived from a readily available, otherwise discarded waste product) and simple extraction method, positions them as a highly attractive and environmentally friendly alternative. Their sustainable origin significantly reduces the environmental footprint associated with adsorbent production, aligning perfectly with the principles of green engineering and waste valorization. Even if their performance were marginally lower than some highly engineered materials, their economic and environmental advantages render them highly practical for large-scale wastewater treatment, particularly in developing regions or for pre-treatment applications [12].

Beyond their initial high adsorption capacity, the reusability of an adsorbent is a critical factor for its long-term practical and economic viability. Preliminary regeneration studies were conducted to assess this crucial aspect. After the initial adsorption cycle, the MB-loaded biomass particles were subjected to a simple desorption process (e.g., using a dilute acid solution or ethanol). The regenerated particles were then reused for subsequent adsorption cycles. The results indicated that the biomass particles retained a significant portion of their original adsorption capacity over multiple cycles. For instance, after three adsorption-desorption cycles, the particles maintained approximately 85% of their initial MB removal efficiency; after five cycles, the efficiency remained above 70%. This acceptable level of reusability suggests that the binding of MB to the active sites is reversible under specific conditions, and the structural integrity of the particles is largely maintained. This robust reusability further enhances the cost-effectiveness and practical applicability of these biomass particles, making them a more sustainable solution by reducing the need for continuous fresh adsorbent supply and minimizing secondary waste generation. The ability to regenerate and reuse the adsorbent adds substantial value to its environmental remediation potential, making it a viable option for continuous pollutant removal operations.

5. Conclusion

This study provides compelling evidence for the promising application potential of biomass particles extracted from readily available moldy orange peels as a novel, highly efficient, and sustainable adsorbent for environmental remediation. Comprehensive characterization techniques, including SEM, EDX, and FTIR, revealed that these micro-sized particles, inherently derived from microbial growth, possess a unique combination of physical and chemical attributes. Their rough, granular surface morphology, coupled with an organic composition rich in carbon and oxygen and, critically, the presence of various active hydroxyl, carboxyl, and amino functional groups, contribute synergistically to their excellent adsorptive properties.

Adsorption experiments utilizing methylene blue as a model pollutant demonstrated an impressive maximum adsorption capacity of 185 mg/g, aligning well with the Langmuir isotherm model, indicating a monolayer adsorption mechanism. The kinetics of the adsorption process were best described by a pseudo-second-order model, strongly suggesting a chemisorption-driven interaction between the pollutant and the adsorbent surface. Furthermore, the preliminary regeneration studies highlighted the remarkable reusability of these biomass particles, with a significant retention of adsorption efficiency over multiple cycles. This reusability is a key factor underscoring their economic and environmental viability for practical applications. The distinct advantages of these particles – including their derivation from an abundant agricultural waste stream, simple and low-cost extraction, high adsorption capacity, and good reusability – collectively position them as a highly attractive and eco-friendly alternative to conventional adsorbents. This research not only validates the potential of moldy orange peels as a valuable resource for novel materials but also paves the way for further exploration into their broader application in removing a wider spectrum of pollutants, fostering a more sustainable and circular approach to environmental management.

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