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A Comprehensive Analysis of Natural Honeycomb: Structure, Function, Dye adsorption and Applications

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ABSTRACT

Honeycomb structures, renowned for their remarkable combination of strength, lightweight nature, and efficient space utilization, are found ubiquitously in both natural and engineered settings. With origins in biological systems—most notably within bee hives and plant tissues—these hexagonal cell configurations have captivated the attention of scientists and engineers alike due to their inherent stability and multifaceted potential applications. This study provides an in-depth exploration of honeycomb structures, examining their historical evolution, intricate geometry, and unique mechanical properties that contribute to their robustness and adaptability. Beyond structural applications, natural honeycomb exhibits exceptional adsorption capabilities, positioning it as a promising adsorbent for environmental and industrial applications. This paper investigates the physical and chemical attributes of honeycomb that enhance its effectiveness in adsorbing diverse pollutants, including heavy metals, organic compounds, and airborne contaminants. Experimental analyses are presented to evaluate its adsorption efficiency across various substances, elucidating key factors such as surface area, pore distribution, and chemical functional groups that contribute to its high adsorption performance. The findings underscore the versatility of honeycomb structures as sustainable and efficient adsorbents, highlighting their potential across diverse fields such as environmental remediation, biomedical engineering, and advanced material design. By expanding our understanding of honeycomb's adsorption mechanisms and exploring potential technological applications, this study contributes valuable insights into harnessing natural architectures for innovative scientific and industrial solutions.

Keywords: Structure, Functional groups, Properties, Application, Silanization.

1. INTRODUCTION

The discovery and study of honeycomb structures have yielded profound insights into natural architecture and inspired innovations across various disciplines. In nature, honeycomb structures are prominently exemplified by the intricate hexagonal cells of bee hives and the cellular arrangements in plant tissues. Bees assemble hexagonal wax cells with remarkable precision and structural integrity through innate biological processes, making these formations not only marvels of biological engineering but also crucial structures supporting the colony's activities.

For decades, scientists and engineers have also been fascinated by the geometric perfection of honeycomb constructions. The hexagonal design is a testimony to nature's capacity to create maximum strength with the least material utilization since it offers ideal packing efficiency and resilience. The mechanical characteristics of honeycomb structures, which have exceptional strength-to-weight ratios and are perfect for lightweight and durable applications, are very efficient.

Beyond its mechanical and biological characteristics, honeycomb structures have wholly changed several sectors. For example, honeycomb core materials are now essential parts of composite materials used in spacecraft and aeroplane constructions in aerospace engineering. Honeycomb constructions are lightweight and very strong, significantly lowering fuel consumption and improving overall efficiency. Lightweight building materials and energy-efficient buildings are examples of the breakthroughs in the architectural and construction disciplines brought about by ideas influenced by honeycombs. Honeycomb structures are beneficial in various applications, from protective panels to environmentally friendly housing options, due to their ability to distribute weights uniformly and resist external pressures.

Moreover, the biomimetic potential of honeycomb structures extends into biomedical and materials science domains. Researchers have explored replicating honeycomb architectures in synthetic materials for applications in tissue engineering, drug delivery systems, and filtration technologies. These endeavours seek to mimic nature's design principles and aim to harness honeycomb structures' unique properties for advancing human health and environmental sustainability.

Silanization is a surface modification technique commonly used to functionalize materials with silane coupling agents. These agents contain a reactive silane group (Si-OR) that chemically bonds to the substrate surface (e.g., silica, ceramics, metals)

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through hydrolysis and condensation reactions. Silanization introduces functional groups, such as amino (-NH2), hydroxyl (-OH), or epoxy (-OCH_3), which alter surface properties and enhance specific interactions with target molecules, including dyes in adsorption applications.

This paper aims to comprehensively explore the structure, formation mechanisms, mechanical properties, adsorption capabilities and diverse applications of honeycomb structures. By synthesizing current knowledge and highlighting emerging trends, this study underscores the profound impact of honeycomb structures on technological advancements, ecological sustainability, and interdisciplinary research endeavours.

2. STRUCTURE OF HONEYCOMB

The honeycomb structure (Hepburn *et al.* 2015; Kundu *et al.* 2013) is characterized by a regular arrangement of hexagonal cells, resembling a closely packed array of six-sided prisms. This geometric configuration is nature's solution to achieving optimal efficiency in space utilization and material strength.

2.1 Hexagonal Cells

Each cell within a honeycomb structure (Hepburn *et al.* 2015; Kundu *et al.* 2013). is a hexagon, defined by six equal sides and internal angles of 120 degrees. This shape is inherently stable and provides maximum volume for a given perimeter, making it highly efficient for storage and structural purposes. The hexagonal symmetry also facilitates the uniform distribution of stresses, enhancing the overall mechanical integrity of the structure.

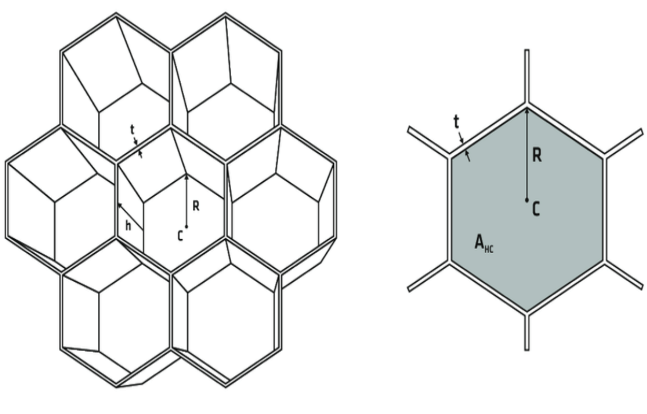

Fig. 1 Regular hexagonhoneycomb structure

The elastic properties of Regular hexagon honeycomb structure depend on the A_{HC} and the thickness t of the supports (Reference: Airborne testing of molded polymer compounds Daniel KOTSCHATE1, Saskia WENDLAND1,2 and Mate GAAL1 1Bundesanstalt fur Materialforschung und -pr ¨ufung (BAM), Germany¨ 2Technical University of Ilmenau, Germany).

2.2 Why Hexagons?

2.2.1 Efficiency In Space Usage

Tiling Efficiency: Hexagons are one of the three shapes that can tile a plane without leaving any gaps (the other two being triangles and squares). This means that hexagons fill space most efficiently, maximizing the use of the available area.

Storage Optimization: By constructing hexagonal cells, bees can store the maximum amount of honey while using the least amount of wax. This is crucial for the hive's sustainability and productivity.

2.2.2. Structural Strength

Load Distribution: The hexagonal pattern distributes weight evenly, providing strength and stability to the structure. Each cell shares its walls with adjoining cells, allowing the honeycomb to support significant weight without collapsing (Chou *et al.*1993).

Geometric Stability: Hexagons are more robust than other shapes such as squares or triangles due to their geometry. The angles and equal sides of hexagons contribute to the overall structural integrity, making the honeycomb durable and resilient.

2.2.3 Energy Efficiency

Material Economy: Bees use wax, which is energetically costly to produce. The hexagonal structure minimizes the amount of wax needed per cell, conserving energy and resources.

Thermoregulation: The efficient packing of hexagonal cells aids in maintaining the hive's internal temperature, which is critical for developing larvae and storinge of honey.

2.2.4 Construction Process

- Secretion and Moulding: Worker bees secrete beeswax from special glands on their abdomen. They then chew and mould the wax into hexagonal cells, starting from a central point and expanding outward.
- Coordination and Precision: The construction of a honeycomb is a highly coordinated effort involving thousands of worker bees. Despite the lack of centralized control, bees instinctively build cells that are uniform in size and shape.

2.2.5 Mathematical And Physical Insights

- Minimal Surface Area: The hexagonal structure provides the least surface area (Gosset *al.* 2020) for a given volume, which is why it requires less wax.
- Geometric Efficiency: Mathematically, hexagons are the most efficient shape for dividing a surface into regions of equal area with the least total perimeter.

2.3 Material Compositon

2.3.1 Beeswax

Secretion: Beeswax is secreted by worker bees from glands located on their abdomens (Tulloch (1980).

Malleability: Beeswax is pliable when secreted, allowing bees to mould it into the desired shape before it hardens.

2.3.2 Building Process

Initialization: Bees start constructing the comb from a central point, expanding outward in a circular fashion.

Coordination: Thousands of worker bees collaborate, each contributing to the construction with remarkable precision.

2.3.3 Cell Formation

Chewing and Shaping: Bees chew the wax to soften it and then use their mandibles to shape the hexagonal cells.

Heat Application: Bees use the heat generated from their bodies to keep the wax malleable during construction.

2.3.4 Material Composition

Beeswax is the primary material used by honeybees to build their combs. It is secreted by worker bees from glands located on their abdomen. The composition of beeswax includes various organic compounds (Bogdanov, 2009).

- Hydrocarbons: Approximately 14% of beeswax consists of hydrocarbons, which contribute to its hydrophobic properties, making it water-resistant.
- Monoesters: Making up about 35% of beeswax, monoesters are compounds formed from fatty acids and long-chain alcohols. These contribute to the rigidity and structure of the wax.
- Diesters: Around 14% of beeswax consists of diesters, which also help maintain the honeycomb's structural integrity.
- Hydroxy polyesters: These compounds, making up around 8%, provide additional strength to the wax.
- Free acids: Approximately 12% of beeswax is composed of free fatty acids, which can act as plasticizers, giving the wax some flexibility.
- Other components: The remaining percentage includes alcohols, pigments, and aromatic substances that contribute to the colour and odour of beeswax.

2.4 Geometric Arrangement

2.4.1 Hexagonal Structure

The primary geometric feature of a honeycomb is the hexagonal cell. Each cell is a hexagon, which is a six-sided polygon with equal-length sides and equal interior angles of 120 degrees. This arrangement is notable for several reasons:

- Efficiency in Space Utilization: Hexagons fit together perfectly without leaving any gaps, which maximizes the use of available space. This packing efficiency is superior to other shapes like squares or triangles.
- Material Minimization: The hexagonal structure requires the least amount of material (beeswax) to construct a given volume compared to other shapes. This is crucial for bees as it conserves their energy and resources.
- Structural Strength: The shared walls of the hexagonal cells provide excellent structural stability. Each cell supports its neighbours, distributing stress and weight evenly throughout the honeycomb.

2.4.2 Mathematical Properties

The geometry of hexagonal cells has several mathematical properties that contribute to the overall efficiency and functionality of the honeycomb:

- Area Maximization: The hexagon encloses the maximum possible area for a given perimeter length. This means that bees can store the most honey and pollen while using the least amount of wax to build the walls.
- Angle Optimization: The 120-degree angles of the hexagonal cells allow for an even distribution of forces, enhancing the structural integrity of the honeycomb.
- Volume-to-Surface Ratio: The hexagonal structure optimizes the volume-to-surface ratio, which is beneficial for thermal regulation and insulation within the hive.

2.4.3 3d Arrangement

While the two-dimensional arrangement of hexagonal cells is a defining characteristic, the honeycomb also exhibits a three-dimensional aspect (Hailun Zhou *et al.* 2024)

- Vertical Stacking: Honeycomb cells are often vertically stacked in layers, with each layer offset from the one above it. This arrangement further enhances the strength and stability of the honeycomb.
- Angles and Tilts: Honeycomb cells are typically tilted slightly upwards (by about 9-14 degrees) to prevent the honey and nectar from dripping out. This slight angle ensures that gravity helps keep the stored resources within the cells.

2.4.4 Functional Advantage

The geometric arrangement of the honeycomb provides several functional advantages:

- Load Distribution: The hexagonal cells evenly distribute the hive's weight and contents, preventing localized stress points that could lead to structural failure.
- Thermal Regulation: The close packing of cells and the efficient use of space contribute to the thermal regulation within the hive. Bees can maintain a stable internal temperature, crucial for brood development and colony health.
- Flexibility and Repair: The modular nature of the hexagonal cells allows bees to easily add, remove, or repair individual cells without compromising the integrity of the entire structure.

2.5 Scalability And Adaptability

2.5.1 Scalability

Scalability refers to the ability of a system to maintain its functionality and efficiency when expanded or reduced in size. Honeycomb structures excel in this regard due to several inherent characteristics:

2.5.1 a) Modular Design

Incremental Growth: Honeycomb structures can grow incrementally. Bees can add new cells to the edges of the existing structure without disrupting the overall integrity. This modularity is beneficial in engineered applications, allowing for the easy expansion or reduction of structures.

Repetition of Units: The repeating hexagonal units allow for straightforward scaling. Whether the structure is expanded to cover a large area or reduced for small-scale applications, the fundamental unit—the hexagonal cell remains unchanged in its design and function.

2.5.1 b) Efficiency Retention

Material Efficiency: The efficiency of material usage is retained regardless of the scale. The hexagonal arrangement ensures minimal material use while maintaining strength, whether in small or large structures.

Structural Integrity: The geometric arrangement maintains its load-distribution properties at all scales. This means that large honeycomb structures can bear significant loads just as efficiently as smaller ones.

2.5.1 c) Versatile Applications

Engineering and Architecture: Honeycomb structures are used on various scales, from microscopic applications in materials science to large-scale architectural designs. The ability to scale without losing efficiency makes honeycomb structures ideal for diverse applications.

2.5.2 Adaptability

Adaptability refers to the ability of a system to adjust to different conditions or environments. Honeycomb structures are highly adaptable due to their inherent properties:

2.5.2 a) Material Variability

Natural Adaptations: In nature, bees can modify the composition of the wax to adapt to different environmental conditions. For example, the wax can be made softer or harder depending on temperature variations.

Engineered Materials: In industrial applications, honeycomb structures can be made from various materials such as metals, plastics, and composites. This flexibility allows the structure to be tailored to specific requirements, such as increased thermal resistance or enhanced strength.

2.5.2 b) Geometric Flexibility

Shape Adaptations: While the basic unit of a honeycomb is the hexagonal cell, these cells can be adapted to different shapes and configurations to meet specific needs. For instance, re-entrant or auxetic honeycomb structures exhibit unique properties like negative Poisson's ratio, which can be beneficial in specialized applications.

Orientation Adjustments: The orientation and alignment of the cells can be adjusted to optimize the structure for different loads and stresses. This adaptability ensures that the honeycomb structure can be customized for various applications, from aerospace engineering to biomedical devices.

2.5.2 c) Functional Versatility

Multi-Functional Use: Honeycomb structures can serve multiple functions simultaneously. A beehive uses the same structure for storing honey, rearing brood, and regulating temperature. Similarly, honeycomb structures can provide thermal insulation, acoustic dampening, and mechanical support in engineered applications.

Environmental Adaptation: Honeycomb structures can be designed to adapt to different environmental conditions. For example, honeycomb panels can be designed to withstand extreme temperatures and pressures in aerospace applications.

2.6 Evolutionary Advantage

2.6.1 Efficiency In Resource Utilization

2.6.1 a) Material Efficiency

Minimal Wax Usage: The hexagonal design of the honeycomb uses the least amount of beeswax to construct cells with maximum volume. This efficient use of materials allows bees to conserve energy and resources, which are critical for the colony's survival.

Energy Conservation: By minimizing the amount of wax required, bees can invest more energy in foraging and reproduction, enhancing the overall productivity and sustainability of the colony.

2.6.1 b) Space Optimization

Maximal Storage: The hexagonal cells fit together perfectly without leaving gaps, maximizing the use of available space within the hive. This allows bees to store more honey, pollen, and brood in a compact area, which is crucial for maintaining a large and healthy colony

2.6.2 Structural Strength And Stability

2.6.2 a) Load Distribution

Even Stress Distribution: The hexagonal cells distribute stress evenly throughout the structure, providing exceptional stability and resistance to external forces. This design helps the honeycomb withstand the weight of stored honey and the dynamic activities of the bees

Resilience: The interconnected nature of the cells means that damage to one part of the honeycomb has minimal impact on the overall structure, ensuring the integrity of the hive remains intact.

2.6.2 b) Thermal Regulation

Insulation: The dense packing of the hexagonal cells provides excellent insulation, helping to maintain a stable internal temperature within the hive. This is vital for brood development and the overall health of the colony (Jones & Oldroyd, 2006).

2.6.3 Versatility And Functionality

2.6.3 a) Multipurpose Use

Brood Rearing: The cells of the honeycomb serve as nurseries where the queen lays eggs and the larvae develop. The uniform size of the cells ensures consistent development conditions for the brood.

Food Storage: The same cells used for brood rearing can also store honey and pollen. This multipurpose use of the honeycomb cells increases the efficiency of space utilization within the hive.

2.6.3 b) Adaptability To Environmental Conditions

Dynamic Construction: Bees can adjust the size and shape of the honeycomb cells to adapt to different environmental conditions and colony needs. For example, they can build larger cells for drone brood or reinforce cells to provide additional support in response to environmental stresses

2.6.4 Evolutionary Success

2.6.4 a) Survival And Reproduction

Colony Efficiency: The efficiency and robustness of the honeycomb structure contribute significantly to the survival and reproductive success of the bee colony. Honeycomb structures enhance the colony's overall fitness by optimizing resource use and providing a stable environment for brood development.

Selective Advantage: Over evolutionary time, colonies that utilized the honeycomb structure more efficiently were more likely to survive and reproduce, passing on genes favouring this advantageous design.

2.6.5 Methodologies For Studying Honeycomb Structures

Various experimental and computational methods have been employed to study the properties of natural honeycombs. This section reviews the techniques used to analyze the structural and mechanical properties of honeycombs, including:

1. Mechanical Testing: Methods such as compression and shear tests to determine strength and stiffness.
   - Compression Testing: Measures how the honeycomb structure deforms under compressive loads. Provides data on the material's strength and stiffness.
   - Shear Testing: Evaluates the material's resistance to shear forces, which is critical for understanding how the structure behaves under lateral loads.
2. Image Segmentation: Techniques for analysing the size and geometry of honeycomb cells.
   - Image Analysis: High-resolution images of honeycomb structures are analyzed to measure cell dimensions and identify patterns. This helps in understanding the uniformity and precision of the natural construction.
3. Finite Element Analysis (FEA): Computational methods to simulate the behaviour of honeycombs under different loading conditions.
   - Simulation Models: FEA models simulate how honeycomb structures respond to various forces. This helps predict performance and identify potential failure points without physical testing.

3. FORMATION MECHANISM

The formation of the honeycomb is a complex process that involves the coordinated activities of honeybees, utilizing their biological and behavioural adaptations to create a highly efficient and structurally sound structure. This section explores the mechanisms involved in the formation of honeycomb, detailing the biological processes, behavioral patterns, and the roles of different types of bees within the hive.

3.1 Biological Processes

3.1 a) Beeswax Production

Secretion of Wax: Worker bees have specialized wax glands located on the underside of their abdomen. These glands secrete liquid wax, which hardens into tiny scales as it comes into contact with the air.

Wax Manipulation: Bees use their mandibles to collect the wax scales and manipulate them into shape. The bees chew the wax to soften it, making it malleable for construction.

3.1. b)Chemical Composition

Beeswax Composition: Beeswax is composed of various organic compounds, including hydrocarbons, monoesters, diesters, hydroxy polyesters, and free acids. This composition provides the wax with its structural properties, such as rigidity and plasticity.

3.2 Behavioural Patterns

3.2 a) Temperature Regulation

Optimal Building Temperature: Bees maintain the hive temperature between 32-36°C (90-97°F), which is the optimal range for beeswax manipulation. Worker bees generate heat through muscle activity to maintain this temperature, ensuring the wax remains pliable for construction (Brown *et al.* 2016).

3.2 b) Collective Building Behaviour

Coordination and Communication: Bees communicate through pheromones and the "waggle dance," which helps coordinate the building process. They work collectively, with each bee performing specific tasks such as secreting wax, shaping cells, or measuring distances.

Cell Construction: The construction of a honeycomb begins at a central point and progresses outward. Bees start by building vertical sheets of wax with hexagonal cells on both sides. They use their legs and mandibles to shape and connect the cells precisely.

3.2 c) Hexagonal Cell Formation

Natural Geometry: The hexagonal shape of the cells emerges naturally as bees construct the comb. While the exact mechanism is not fully understood, it is believed that the physical properties of wax and the bees' building behaviour led to the formation of hexagons. The hexagonal shape is the most efficient in terms of space and material usage.

4. MECHANICAL PROPERTIES

4.1 High Strength-To-Weight Ratio

Natural honeycombs, such as those built by bees, exhibit a remarkably high strength-to-weight ratio. This property is primarily due to the hexagonal structure, which provides optimal load distribution while minimizing the amount of material used. The thin walls of the hexagons offer substantial strength without adding much weight. This efficiency is a key reason why honeycomb structures are mimicked in engineering applications (Chou *et al.*1993; Garcia *et al.* 2024), such as in aerospace, for constructing lightweight yet strong panels.

4.2 Energy Absorption

Honeycombs are highly effective at absorbing energy, which makes them excellent for impact resistance. When subjected to an impact, the cells can deform, absorbing and dissipating the energy throughout the structure. This energy absorption capability is why honeycomb structures are used in protective gear, automotive crash zones, and packaging materials to cushion and protect contents.

4.3 Elasticity And Flexibility

The hexagonal cells of a honeycomb provide a degree of elasticity and flexibility. This means that the structure can undergo deformation under stress and then return to its original shape when the stress is removed. This elastic behaviour is due to the geometric arrangement (Gibson *et al.* 1997) and the material properties of the cell walls, which can bend and flex without breaking.

4.4 Crush Strength

The ability of honeycomb structures to resist crushing forces is one of their notable mechanical properties. The geometry of the hexagonal cells distributes compressive loads evenly, making the structure highly resistant to crushing. This property is essential for maintaining structural integrity under heavy loads, and it is particularly advantageous in applications requiring compression resistance, such as in construction materials.

4.5 Thermal Insulation

Honeycomb structures provide excellent thermal insulation due to the air trapped within the cells. Air is a poor conductor of heat, and the numerous small pockets within the honeycomb reduce heat transfer through the material. This makes honeycombs useful in applications requiring thermal insulation, such as building materials and packaging that need maintaining temperature control.

4.6 Fracture Toughness

Natural honeycombs exhibit high fracture toughness, which is the ability to resist the propagation of cracks. The interconnected hexagonal cells help distribute stress and prevent stress concentration at any single point. This distribution reduces the likelihood of crack formation and propagation, enhancing the durability and longevity of the structure.

4.7 Lightweight

One of the most significant advantages of honeycomb structures is their lightweight nature. The minimal use of material in the thin walls of the hexagonal cells results in a very low density. This lightweight characteristic is crucial in applications where weight reduction is critical, such as aerospace, automotive, and sports equipment. The lightweight nature of honeycombs contributes to energy efficiency and ease of handling (Garcia *et al*. 2024).

4.8 Acoustic Properties

Honeycomb structures can also have beneficial acoustic properties. The air pockets within the cells can dampen sound waves, providing sound insulation and noise reduction. This makes honeycombs useful in applications where sound control is important, such as in building construction, acoustic panels, and automotive interiors (Brown *et al.* 2016; Smith *et al.*2024).

5. FUNCTIONAL GROUPS PRESENT ON THE HONEYCOMB

5.1 Esters: Esters Are Formed By The Reaction Of Carboxylic Acids And Alcohols

General formula: RCOOR'
Example: Myricyl palmitate.
Chemical formula: $CH_3(CH_2)_{14}COOCH_2(CH_2)_{28}CH_3$

5.2 Hydrocarbons

Hydrocarbons in beeswax are primarily long-chain alkanes.
General Structure: C-H
Example: n-Pentacosane
Chemical Structure:$CH_3(CH_2)_{23}CH_3$

5.3 Free Fatty Acids

Free fatty acids are carboxylic acids with long hydrocarbon chains.
General Structure: RCOOH
Example: Palmitic Acid
Chemical Structure: $CH_3(CH_2)_{14}COOH$

5.4 Alcohols

Primary alcohols in beeswax have a hydroxyl group (-OH) attached to a long hydrocarbon chain.
General Structure: R-OH
Example: Myricyl Alcohol
Structure: $CH_3(CH_2)_{29}CH_2OH$

5.5 Ketones

Ketones have a carbonyl group (C=O) bonded to two carbon atoms.
General Structure: RCOR'
Example: Triacontan-1-one
Structure:$CH_3(CH_2)_{28}COCH_3$

5.6 Aldehydes

Aldehydes contain a carbonyl group bonded to at least one hydrogen atom.
General Structure: RCHO
Example: Nonanal
Structure: $CH_3(CH_2)_7CHO$

5.7 Sterols

Sterols are complex alcohols with a multi-ring structure.
Example: Cholesterol
Structure: $C_{27}H_{45}OH$

6. CHEMICAL MODIFICATIONS FOR ENHANCED DYE ADSORPTION ON HONEYCOMB

6.1 Surface Functionalization

6.1 1) Silanization

Silanization is a surface modification (Zhang et al. 2020) technique commonly used to functionalize materials with silane coupling agents. These agents contain a reactive silane group (Si-OR) that chemically bonds to the substrate surface (e.g., silica, ceramics, metals) through hydrolysis and condensation reactions. Silanization introduces functional groups, such as amino (-NH2), hydroxyl (-OH), or epoxy (-OCH3), which alter surface properties and enhance specific interactions with target molecules, including dyes in adsorption applications (Chen *et al.* 2018).

Silanization Process For Honeycomb Structures

6.1.1 A) Silane Coupling Agents

Various silane coupling agents (Zhang *et al.* 2016) are available depending on the desired surface functionality:

(i) Aminosilanes (e.g., 3-aminopropyltriethoxysilane (APTES)): Introduce amino (-NH2) groups that can participate in hydrogen bonding and electrostatic interactions with dye molecules, improving adsorption affinity.

(ii)Epoxysilanes (e.g., glycidyloxypropyltrimethoxysilane (GPTMS): Provide epoxy (-OCH3) groups that can undergo ring-opening reactions, enhancing surface reactivity and adsorption capacity.

(iii)Methacrylatesilanes(e.g.,3-(trimethoxysilyl)propylmethacrylate(MEMO): Introduce methacrylate groups that can polymerize and form cross-linked networks, improving mechanical stability and durability.

6.1.1 B) Application Method

Silane coupling agents are typically applied via solution deposition, vapor deposition, or aerosol spraying onto the honeycomb surface. The agents undergo hydrolysis in the presence of water vapor or a catalyst, forming silanol groups that subsequently condense to form stable siloxane bonds with the substrate.

6.1.1 C) Carboxylation

Introduce carboxyl (-COOH) groups onto the surface using treatments such as plasma activation or chemical derivatization. Carboxyl groups enhance adsorption through ion exchange and electrostatic interactions with dye molecules.

Advantages of Silanization

(i) Enhanced Surface Functionality: Silanization modifies honeycomb surfaces to increase surface area and introduce specific functional groups that enhance adsorption interactions with dyes.

(ii)Improved Adsorption Capacity: Functional groups introduced through silanization enhance the binding affinity and selectivity of honeycomb structures towards target pollutants, including dyes, in aqueous solutions.

(iii)Chemical and Mechanical Stability: Silane coupling agents form covalent bonds with the substrate, providing chemical stability against harsh environmental conditions and mechanical stability under operational stresses.

6.2 Ionic Modification

(i) Ion Exchange Resins: Modify the honeycomb material to incorporate ion exchange resins, such as sulfonated or aminated resins, which selectively bind dye molecules based on charge interactions.

(ii) Quaternization: Quaternary ammonium salts (e.g., trimethylamine) can be anchored onto the honeycomb surface to introduce positively charged sites, enhancing electrostatic attraction to negatively charged dyes.

6.3 Metal Ion Immobilization

(i) Chelation: Immobilize metal ions (e.g., Fe3+, Cu2+) onto the honeycomb surface through complexation with ligands like EDTA or polyamines. Metal ions can act as active sites for dye adsorption through coordination bonds.

(ii)Metal Oxides: Deposit metal oxides (e.g., titanium dioxide) onto the honeycomb surface to create photocatalytic sites that degrade dyes after adsorption, enhancing overall dye removal efficiency.

6.4 Polymer Coatings

(i)Polymeric Layers: Apply thin polymeric coatings (Wang et al. 2017) (e.g., polyaniline, polyethyleneimine) onto the honeycomb surface to create a porous matrix that traps dye molecules through physical entrapment or chemical interactions.

(ii)Cross-linking Agents: Use cross-linking agents (e.g., glutaraldehyde) to immobilize polymers onto the honeycomb surface, enhancing the stability and durability of the adsorption sites.

6.5 Surface Roughening

Micro- and Nano-structuring: Create hierarchical surface structures (micro and nanostructures) on the honeycomb surface using etching or plasma treatment techniques. These structures increase surface area and provide more binding sites for dye molecules.

6.6 Functional Nanomaterial Incorporation

(i)Graphene Oxide or Carbon Nanotubes: Incorporate graphene oxide or carbon nanotubes onto the honeycomb surface to enhance adsorption capacity through π-π interactions and increased surface area.

(ii)Metal-Organic Frameworks (MOFs): Integrate MOFs (Nguyen et al. 2021) onto the honeycomb structure to create highly porous materials with tailored pore sizes and specific adsorption sites for dyes.

7. APPLICATIONS IN DYE ADSORPTION

- Environmental Remediation (Harris et al. 2019): Silanized honeycomb structures are used in wastewater treatment to remove dyes from textile effluents, pharmaceutical wastes, and industrial discharges.
- Selective Adsorption: Aminosilane-functionalized honeycombs exhibit selective adsorption properties, removing specific dyes based on electrostatic interactions and hydrogen bonding.

The removal of synthetic dyes from wastewater is a critical environmental challenge due to the toxic and non-biodegradable nature of these dyes. Adsorption has emerged as an effective and economical method for dye removal (Xu *et al.* 2017). Here the various adsorbents used for dye adsorption, including activated carbons, biosorbents, and novel materials like nanocomposites. The mechanisms of adsorption, factors affecting adsorption efficiency, and the potential for regeneration and reuse of adsorbents are discussed.

The discharge of dye-laden effluents from industries such as textiles, leather, and cosmetics poses significant environmental and health risks. Synthetic dyes are resistant to degradation and can cause serious environmental pollution. Among various treatment methods, adsorption has gained prominence due to its simplicity, cost-effectiveness, and high efficiency.

7.1 Types Of Adsorbents

7.1 A) Activated Carbons

Activated carbon is the most widely used adsorbent for dye removal due to its high surface area, porous structure, and significant adsorption capacity. Activated carbons can be derived from various precursors such as coal, coconut shells, and wood.

Advantages:
High adsorption capacity
- Large surface area
- Availability of raw materials

Disadvantages:
- High production costs
- Difficulty in regeneration

7.1 B) Biosorbents

Biosorbents are materials of biological origin, such as agricultural wastes, algae, fungi, and bacteria. These materials are eco-friendly and cost-effective alternatives to activated carbons (Gupta *et al.* 2009).

Advantages
- Low cost
- Biodegradability
- Abundance of raw materials

Disadvantages:
- Lower adsorption capacity compared to activated carbon
- Variability in adsorption performance

7.1 C)Nanocomposites And Novel Materials

Recent research has focused on developing nanocomposites and other novel materials for dye adsorption. These materials often exhibit superior adsorption capacities due to their unique properties.

Examples:
- Carbon nanotubes
- Graphene oxide
- Metal-organic frameworks (MOFs)
- Magnetic nanoparticles

Advantages:
- High surface area
- Enhanced adsorption properties
- Possibility of functionalization

Disadvantages:
- High production costs
- Potential environmental risks

7.2 Mechanism Of Adsorption (Nguyen *et al*. 2021)

The adsorption process involves several mechanisms, including:

7.2 A) Physical Adsorption

The electrostatic force is the basic physical principle that describes interactions between molecules of adsorbent and adsorbate. Electrostatic attraction and repulsion are due to dipole-dipole in tractions, dispersion interaction and hydrogen bonding. A molecule is said to have a dipole moment when there is a net separation of positive and negative charges within the molecule. Molecules such as H2O and NH3 have permanent dipoles because of the configuration of atoms and electrons within them. When the electrostatic forces among the charges of the two molecules are summed, the net dipole-dipole interaction is an attraction between the two polar molecules that tend to attract each other. Hydrogen bonding is a particular case of dipole-dipole interaction in which the hydrogen atoms in a molecule have a partial positive charge and attract an oxygen atom on other water molecules with a partial negative charge. When two neutral molecules that lack permanent dipoles approach each other, a weak polarisation is induced because of quantum mechanical interactions. The net effect is a weak attraction between the molecules, known as dispersion interaction or London or Vander walls forces.

7.2 B) Chemical Adsorption

Chemical adsorption or chemisorption is also based on electrostatic forces. In chemisorption, the attraction between adsorbent and adsorbate approaches that of a covalent chemical bond between two atoms, with a shorter bond length and higher bond energy. Adsorbates bound by chemisorption to a surface generally cannot accumulate at more than one molecular layer or monolayer because of the specificity of the bond between absorbate and surface. The bond may also be specific to particular sites or functional groups on the surface of the adsorbent. These properties have modelling implications.

Chemical absorption or chemisorption involves forces of a chemical nature similar in magnitude to those observed in chemical combinations. Heats of adsorption are high and usually vary from 20 to 100 Kcal/mole. This process is site specific when the intrinsic affinity of sorbet for sorbent exists: Chemisorption may also occur at ambient temperatures. However, when activation energy 5 to 20K Cal/mole or more is involved, then the process is known as “Activated adsorption”. Transition of physical sorption to chemisorption may be possible, particularly at elevated temperatures, when adsorbed molecules acquire sufficient energy to be involved in chemical interaction with the sorbent surface. One of the earliest of evidence of chemisorption’s was provided by Langmuir.

Adsorption has a short history compared to the other processes. Adsorption was first observed in the solution by loweitz in 1785 and was soon applied as a process for the removal of colour from sugar during refining. In the later part of nineteenth century, inactivated charcoal filters were used in American Water Treatment plants.

Generally, adsorption process with activated charcoal attracted many scientists, because of the effectiveness of the removal of dyes at trace quantities. but the high cost of activated carbon limits its full -scale use for removing dyes from high cost of activate carbon limits its full- scale use for removing dyes from waste water. For this reason, the use of low-cost materials as sorbents for the dye removal from waste water has been highlighted, and thus it is necessary to find low-cost adsorbents, which will be economically viable in our country.

7.2 C) Electrostatic Attraction

Electrostatic attraction is one of the primary mechanisms by which adsorption occurs, particularly for ions and polar molecules. This type of adsorption relies on the interaction between charged sites on the adsorbent surface and oppositely charged adsorbate species.

(i) Basic Principles

- Electrostatic Attraction: When an adsorbent surface possesses charged sites, it can attract and hold oppositely charged adsorbate molecules or ions through Coulombic forces. This is known as electrostatic attraction.
- Surface Charge: The surface charge of the adsorbent can be positive or negative, depending on its composition and the pH of the surrounding environment. Adsorbents with a net positive surface charge will attract negatively charged adsorbates (anions), while those with a net negative surface charge will attract positively charged adsorbates (cations).

(ii) Mechanism of Electrostatic Adsorption

- Charged Sites: The adsorbent material, such as natural honeycomb, can develop charged sites through various means. For instance, the presence of functional groups like carboxyl, hydroxyl, or amine groups can contribute to the overall surface charge.
- Ionization: Depending on the pH of the solution, these functional groups can become ionized. For example, carboxyl groups (-COOH) can lose a proton to become negatively charged carboxylate ions ($-COO^-$) in an alkaline environment.
- Attraction and Binding: Once the adsorbent surface is charged, it can attract and bind oppositely charged adsorbate species. For example, a negatively charged surface will attract cations such as metal ions (e.g., Pb^{2+}, Cd^{2+}), while a positively charged surface will attract anions like sulfate (SO_4^{2-}) or nitrate (NO_3^-).

(iii) Factors Affecting Electrostatic Adsorption

- pH of the Solution: The pH of the solution plays a crucial role in determining the charge of both the adsorbent and the adsorbate. It affects the ionization state of functional groups on the adsorbent surface and the speciation of the adsorbate.
- Ionic Strength: The presence of other ions in the solution can influence electrostatic interactions. High ionic strength can shield the electrostatic attractions, reducing the adsorption efficiency.
- Surface Chemistry: The type and density of functional groups on the adsorbent surface influence its charge and, consequently, its ability to attract adsorbates electrostatically.
- Adsorbate Characteristics: The charge, size, and hydration sphere of the adsorbate ions affect how strongly they interact with the adsorbent surface.

(iv) Examples of Electrostatic Adsorption

- Heavy Metal Removal: Adsorbents with negatively charged surfaces can effectively remove positively charged heavy metal ions (Smith et al. 2018) from aqueous solutions through electrostatic attraction.
- Dye Adsorption: Cationic dyes, which possess a positive charge, can be adsorbed onto negatively charged surfaces through electrostatic interactions.
- Pollutant Adsorption: Charged pollutants, such as nitrates or phosphates, can be removed from wastewater using adsorbents with oppositely charged surfaces.

(v) Practical Applications

- Water Treatment: Electrostatic adsorption is widely used in water treatment processes to remove ionic contaminants. Activated carbon, clays, and biomaterials like natural honeycombs can be tailored to possess specific charges for targeted adsorption.
- Environmental Remediation: Electrostatic interactions are harnessed in soil remediation techniques to immobilize and remove charged pollutants.
- Catalysis and Sensor Technology: Adsorbents with tailored surface charges are used in catalysis and sensor technology to selectively adsorb and detect ionic species.

7.2 D) Π-Π Interactions

π-π interactions are non-covalent interactions between aromatic rings. They play a significant role in the adsorption of organic molecules, especially those containing aromatic rings, onto surfaces that also possess aromatic structures. These interactions are common in systems involving activated carbon, graphite, and certain polymers.

(i) Basic Principles of π-π Interactions

- Aromatic Rings: π-π interactions occur between the π-electrons of aromatic rings. Aromatic rings have a delocalized π-electron system above and below the plane of the ring.
- Types of π-π Interactions: There are two main types of π-π interactions:
  - Face-to-Face (π-Stacking): Where the aromatic rings stack parallel to each other.
  - Edge-to-Face (T-Stacking): Where one aromatic ring is perpendicular to another.

(ii) Mechanism of π-π Adsorption

- Adsorbate and Adsorbent: For π-π interactions to occur, both the adsorbate (the molecule being adsorbed) and the adsorbent (the surface) must contain aromatic rings.
- Interaction Mechanism: The π-electrons from the aromatic ring of the adsorbate interact with the π-electrons of the aromatic rings on the adsorbent surface. This interaction stabilizes the adsorbate on the adsorbent surface.
- Orientation: The orientation of the adsorbate molecules relative to the adsorbent surface can influence the strength of the π-π interactions. Face-to-face interactions generally provide stronger binding compared to edge-to-face interactions.

(iii) Factors Affecting π-π Interactions

- Nature of Aromatic Rings: The presence of substituents on the aromatic rings can enhance or reduce π-π interactions. Electron-donating groups (e.g., -OH, $-NH_2$) and electron-withdrawing groups (e.g., $-NO_2$, -COOH) on the aromatic ring can alter the electron density, affecting the strength of the interaction.
- Planarity: The planarity of the aromatic rings influences the effectiveness of π-π stacking. More planar molecules stack better and exhibit stronger interactions.
- Distance and Alignment: The distance between the aromatic rings and their relative alignment is critical for optimal π-π interactions. Typically, a distance of 3.4 Å (angstroms) between the centres of the rings is considered optimal for π-π stacking.

(iv) Examples of π-π Adsorption

- Activated Carbon: Activated carbon has a high surface area with numerous aromatic rings, making it an effective adsorbent for aromatic pollutants like benzene, toluene, and xylene (BTX).
- Graphene and Carbon Nanotubes: These materials exhibit strong π-π interactions with polycyclic aromatic hydrocarbons (PAHs) and other aromatic compounds due to their extensive π-electron systems.
- Polymers: Polymers with aromatic rings in their structure can adsorb aromatic pollutants through π-π interactions.

(v) Applications of π-π Adsorption

- Environmental Remediation: π-π interactions are used in removing aromatic pollutants from water and air. Adsorbents like activated carbon and graphene-based materials are widely used for this purpose.
- Drug Delivery: π-π interactions facilitate the loading of aromatic drugs onto carriers like carbon nanotubes and graphene, improving drug delivery efficiency.
- Chromatography: In reversed-phase chromatography, π-π interactions between the stationary phase and aromatic compounds can influence retention times and separation efficiency.

7.3 Factors Affecting Adsorption Efficiency

(i) pH

The pH of the solution can significantly affect the adsorption process by influencing the charge on the adsorbent surface and the ionization state of the dye molecules.

(ii) Temperature

Temperature can affect the adsorption capacity and the kinetics of the adsorption process. Typically, an increase in temperature enhances the adsorption capacity for endothermic processes.

(iii) Initial Dye Concentration

The initial concentration of the dye in the solution can influence the adsorption capacity, with higher concentrations providing a greater driving force for mass transfer (Davis *et al.* 2020).

(iv) Contact Time

The contact time between the adsorbent and the dye solution is crucial for achieving equilibrium and maximum adsorption capacity.

7.4 Selective Dye Adsorption: Examples

The effectiveness of honeycomb structures in selectively adsorbing specific dyes depends on various factors, including the dye's chemical nature and the properties of the honeycomb material. Here's an overview of some commonly targeted dyes and how they can be selectively adsorbed using honeycomb structures:

7.4 A) Commonly Targeted Dyes

1.Methylene Blue (MB)

○Type: Cationic dye
○Applications: Textile industry, biological staining
○Selective Adsorption: Honeycomb structures functionalized with negatively charged groups (e.g., sulfonic acid groups) can effectively adsorb MB due to electrostatic attraction.

2.Congo Red (CR)

○Type: Anionic dye
○Applications: Textile industry, pH indicator
○Selective Adsorption: Honeycomb structures with positively charged groups (e.g., amine groups) or basic surface properties can selectively adsorb CR.

3.Rhodamine B (RhB)

○Type: Cationic dye
○Applications: Fluorescent dye, biological staining
○Selective Adsorption: Similar to MB, RhB can be adsorbed by honeycomb structures with negatively charged surfaces.

4.Methyl Orange (MO)

○Type: Anionic dye
○Applications: pH indicator, dyeing
○Selective Adsorption: Honeycomb structures with basic or positively charged functional groups can effectively adsorb MO.

5.Crystal Violet (CV)

○Type: Cationic dye
○Applications: Biological staining, dyeing
○Selective Adsorption: Functionalized honeycomb structures with negatively charged groups are suitable for CV adsorption.

7.4 B) Mechanisms Of Selective Adsorption

(i)Electrostatic Interactions: Depending on the charge of the dye (cationic or anionic), honeycomb structures can be modified with oppositely charged functional groups to enhance adsorption through electrostatic attraction.
(ii)Hydrophobic Interactions: Dyes with hydrophobic characteristics can be adsorbed more effectively by hydrophobic surfaces of honeycomb structures.
(iii)Chemical Bonding: Specific functional groups on the honeycomb structure can form chemical bonds with dye molecules, improving selectivity.
(iv)Physical Trapping: The pore size and distribution in honeycomb structures can physically trap dye molecules, particularly when the size of the dye molecules matches the pore size.

7.4 C) Examples Of Honeycomb Adsorbent Materials

(i)Activated Carbon Honeycombs: High surface area and porosity, often used for adsorbing a wide range of dyes (Smith et al. 2018).
(ii)Polymer-Based Honeycombs: Functionalized polymers can be tailored for specific dyes.
(iii)Silica Honeycombs: Functionalized silica with various groups (e.g., amine, thiol) for selective adsorption.
(iv)Metal-Organic Frameworks (MOFs): Highly porous and customizable for specific dyes.

7.4 D) Experimental Considerations

(i)pH: The pH of the solution can affect dye ionization and adsorption efficiency.
(ii)Temperature: Higher temperatures can increase adsorption rates but may affect selectivity.
(iii)Concentration: Initial dye concentration can influence the adsorption capacity and efficiency.

8. ARTIFICIAL INTELLIGENCE (AI)

Recent advancements in the use of artificial intelligence (AI) algorithms to enhance honeycomb structures primarily focus on optimization, predictive modeling, and resilience enhancements, particularly through artificial neural networks (ANNs) and machine learning techniques (Anwar *et al.* 2023; Anwar *et al.* 2024; Shoaib *et al.* 2022; Anwar *et al.* 2024: Anwar *et al.* 202; Anwar *et al.* 202; Anwar *et al.* 2024). Key innovations include data-driven optimization of honeycomb architectures to improve structural integrity and resistance to specific stresses like impacts or compression. AI is utilized to predict material responses under various conditions, automate structural adjustments, and enable high-performance design configurations tailored for practical applications in fields like aerospace, construction, and biomedicine.

9. CONCLUSIONS

This comprehensive study demonstrates the potential of natural honeycomb as an efficient adsorbent material. Its unique structural and chemical properties enable high adsorption capacities for a range of pollutants. The findings suggest that natural honeycomb could be a sustainable and cost-effective solution for environmental remediation efforts. The functional groups present in natural honeycombs, particularly in beeswax, exemplify nature's sophisticated adaptation for structural integrity, water resistance, and ecological sustainability. Understanding these chemical components provides insights into honeycomb formation, bee behaviour, and ecosystem dynamics, underscoring the interconnectedness of biological systems and their material properties in natural habitats. Silanization of honeycomb structures represents a versatile approach to modify surface properties, enhance adsorption capabilities, and tailor materials for specific applications in dye removal and environmental remediation. Further research and development in optimizing Silanization techniques and understanding surface-adsorbate interactions will continue to advance the effectiveness and versatility of silane-modified honeycomb materials in environmental and industrial sectors.

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