Review Article

A brief and general overview on diatoms and their applications

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Abstract:

Diatoms are single-celled, photosynthetic eukaryotic algae, known as Bacillariophyceae, that are important in the ocean's cycle of nutrients and organic matter. There are possibly more than 150,000 varieties of them spread across fresh, brackish, and marine aquatic ecosystems, and they can be found in almost all aquatic habitats. Diatoms also have value to be used in industrial applications because their glass cell wall fossils are sold as diatomite or diatomaceous earth. Diatom silica, is regarded as an important usable biomaterial for energy storage e.g. (Lithium Ion battery, super capacitor, hydrogen and thermal storage) and energy conversion e.g. (solar cells). In addition, diatomite exhibits substantial specified area of surface, thermal stability, and affordability, which provide tremendous benefits and prospects for application as filler in the paper, rubber, ceramic, pharmaceutical industries as well as abrasive material and soil amendment. In the field of water treatment, diatomite is considered as an eco-environmental functional material and effective adsorbent in the treatment of heavy metal-contaminated water because of its high porosity, low density and high specific surface area. In biomedical applications, mesoporous silica has recently demonstrated promising results in drug delivery systems because of its special chemical and physical characteristics, including excellent drug loading capacity, biocompatibility, and large surface area. Currently, basic and applied researchers are still interested in the use of diatoms in nanotechnology functions.

Keywords: diatoms, silica, diatomite, diatom nanotechnology, applications.

1-CELL WALL STRUCTURE

Diatoms are single-celled, photosynthetic eukaryotic algae, known as Bacillariophyceae, that are important in the ocean's cycle of nutrients and organic matter, (**Nelson et al., 1995; Mann, 1999; Raven and White, 2004**). There are possibly more than 150,000 varieties of them spread across fresh, brackish, and marine aquatic ecosystems, and they can be found in almost all aquatic habitats. The physicochemical characteristics of the environment in which diatoms are created can be clearly linked to the composition of the diatom community.

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Around 200,000 distinct species are thought to exist (**Mann and Droop, 1996**). Diatoms are photosynthetic in its nutrition, however others live heterotrophically (**Frankovich *et al.*, 2018**). Although being solitary cells, diatoms can form colonies that are simple or branching, filamentous, and some even have gelatinous tubes around them (**Julius and Theriot, 2010**). The fact that the single cell is contained in siliceous cell wall (frustule), which is composed of two overlapping valves. The upper valve is called epitheca, while the lower valve is the hypotheca. The top, epigirdle, band can slide over the lower one because the lower valve, along with its connected hypogirdle, is just marginally smaller than the upper assembly. Although they are occasionally referred to separately, the two connecting bands are referred to as the girdle that fit together by an expanding connective zone known as the girdle as a whole. The valves have elaborate ornamentation. The siliceous frustule, is the most intriguing aspect of diatoms (**Round *et al.*, 1990**). Both taxonomy and nanotechnology uses depend on the frustules' size, shape, and symmetry (**Round *et al.*, 1990; Gordon *et al.*, 2009**). The two primary views of a diatom frustule under an optical microscope are valve view and girdle view. In contrast to conventional two-dimensional optical micrographs, the majority of diatom frustules have three-dimensional structures. Additionally, the optical light microscope is unable to disclose the frustules' ultrastructure, which is why transmission and scanning electron micrographs are used to describe the frustule in detail and show its nanofeatures (**Round *et al.*, 1990**). In addition, recent research introduced the atomic force microscope as a new tool. Diatom frustules have been identified as multiscalar pores with various sizes, arrangements, and periodicity patterns in porous silica through ultrastructure studies (**Luís *et al.*, 2017**). Diatoms' strong porous silica frustules may be responsible for their success in many watery ecosystems. It was discovered that the mechanical strength, optical properties, and filtration abilities of these materials were determined by the frustule size, pore size, pore distribution patterns, material properties, and frustule design (**Garcia, 2010; De Tommasi, 2016; Ghobara *et al.*, 2015; Losic *et al.*, 2006**). According to how diatom frustule pores and other ultrastructure show under various types of microscopes, there are various terminologies used to describe them (**Round *et al.*, 1990**).

2-SHAPES OF DIATOMS

Diatoms can be spherical and radially symmetrical (centric) or elongate (pennate) with a bilateral plane of symmetry. Although many diatoms are slightly asymmetrical, they typically belong to one of these two types. The peculiar design of the silica valves and girdle served as the basis for the majority, if not all, of the historical classification of diatoms. Centric diatoms displayed distinct morphological features, including valve margin ornamentation that differs from that of the central region, and frustules that are circular in shape and typically connected into long filaments (Plate I,1,2) (Plate I, 3, 4). Certain centric diatom species' frustules displayed three circular undulations (Plate I, 5b). The pennate diatoms' valves are typically long and linear, with transverse rows of patterns along either border. Frustule can be raphed, which is visible on at least one valve (Plate II,4,5 6,7) or it can be straight, solitary, with striae generating pseudoraphe on both valves (Plate II, 1, 2, 3). A valve with raphe and an opposite valve with pseudoraphe are not similarly decorated (Plate II, 7). Valve symmetry around the transapical plane and asymmetry about the apical plane are both possible (Plate III, 1, 2, 3, 4 and 5). The valves of other pennate diatoms are symmetrical about the transapical and apical planes (Plate III, 6-14, Plate IV), while others are depicted by symmetrical valves along the transapical axis and the apical axis (Plate III 12 and Plate VI, 4, 5 and 6). Valves with longitudinal shadow lines or empty gaps (Plate IV, 7 and 9), or those that may have raphes surrounded in siliceous ribs (Plate III, 7, 8, 9, 10 and 11). The valve's central region extending laterally to its edges, where striae are either absent along the lateral margins of the central region (Plate IV, 10) or are present (Plate IV, 1, 2, 3, 4 and 5). Raphe may be contained in a keel on one valve border in some pennatophycean species (Plate V, 5-16). Each valve's two margins may be covered by the keel (Plate VI, 4, 5 and 6) (**Hamed, 2008**).

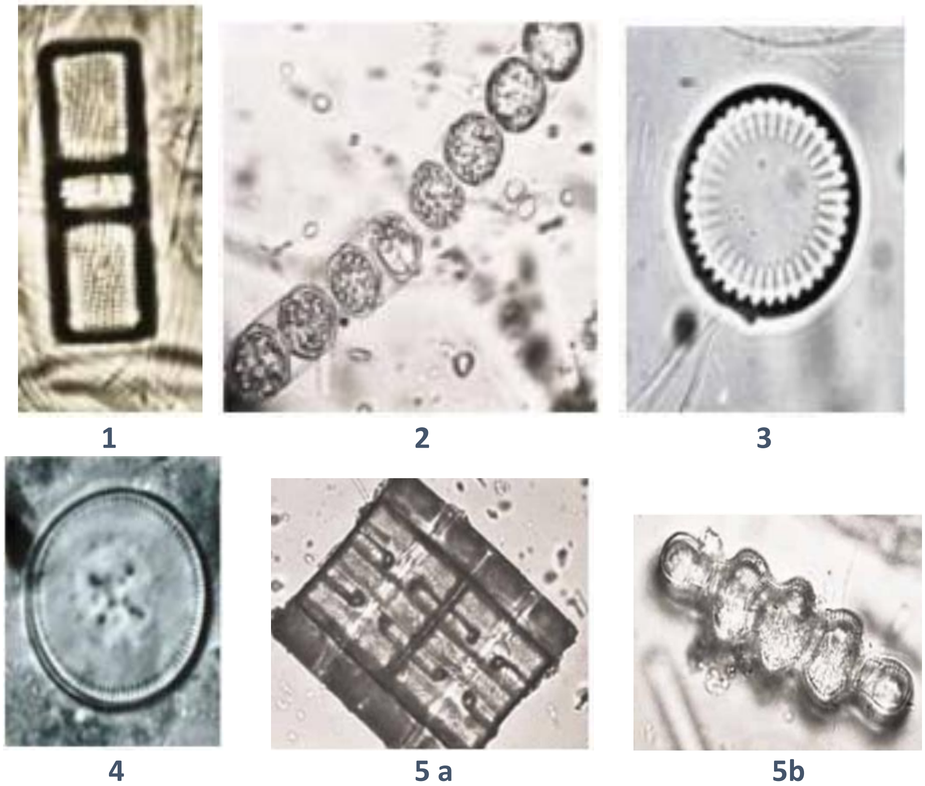

Plate I: 1- *Melosira granulata* (1200X), 2- Melosira *moniliformis* var. *subglobos*a (1200X), 3- *Cyclotella meneghiniana* (1200X), 4- *Cyclotella kützingiana* (1500X), 5a- *Terpsinoe Americana* (700X),5b- *Terpsinoe Americana* (700X).

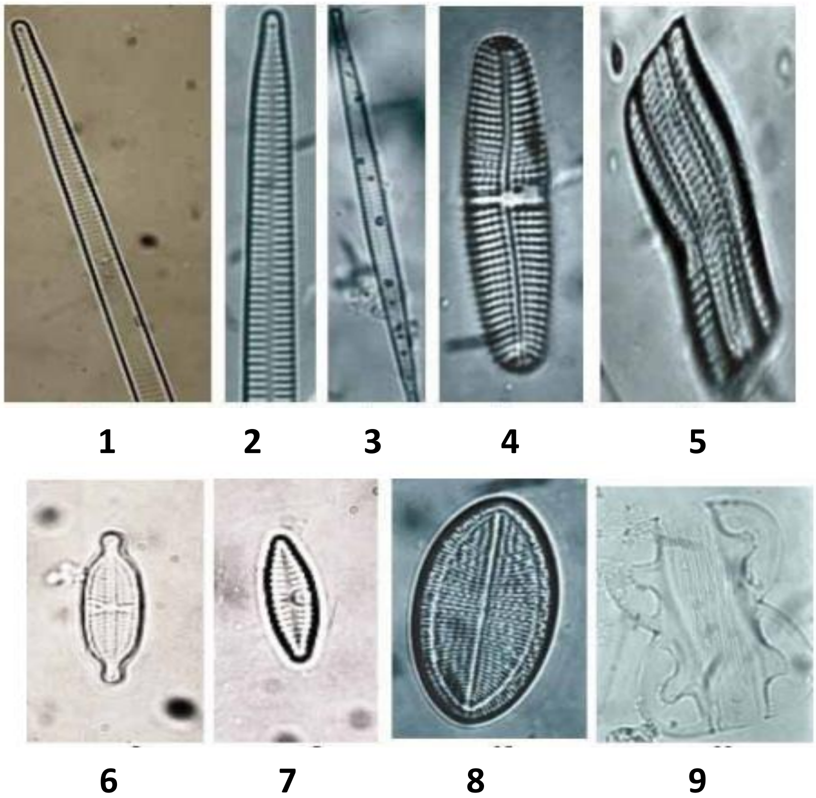

Plate II: *1. - Synedra acus* (1200X), *2-Synedra ulna* (1200X), *3-Synedra tabulate* (1200X), *4,5- Achnanthes brevipes var. intermedia (*1200X),*6- Achnanthes exigua* (1200 X) *7-Achnanthes lanceolata var. rostrata (*1200X), *8- Cocconeis placentula var. euglypta (1200X), 9- Amphiprora paludosa var. subsalina* (900X).

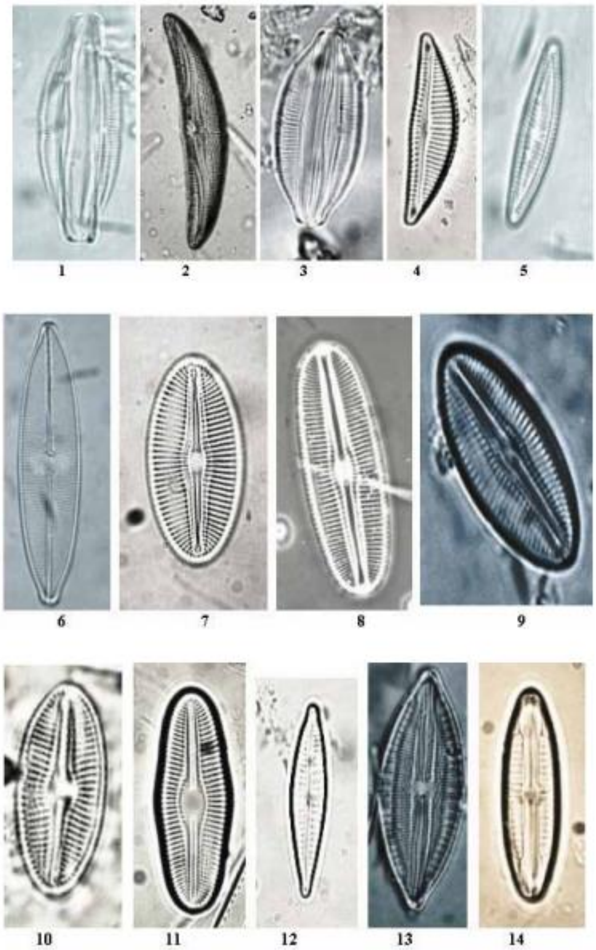

Plate III: *1.Amphora coffeaeformis* (1200 X*), 2.Amphora robusta* (1200X*), 3.Amphora veneta* (1200 X*), 4.Cynbella herbidica* (1200 X*), 5.Cymbella pusilla* (1200 X*), 6.Caloneis bannajensis* (1200 X*), 7.Diploneis elliptica (1200 X), 8.Diploneis oblongella (1200 X), 9.Diploneis ovalis (1200 X), 10.Diploneis pseudovalis (1200 X), 11.Diploneis sp. (1200 X), 12. Gomphonema parvulum (1200 X), 13.Mastogloia smithii (1200 X), 14.Mastogloia braunii (1200 X).*

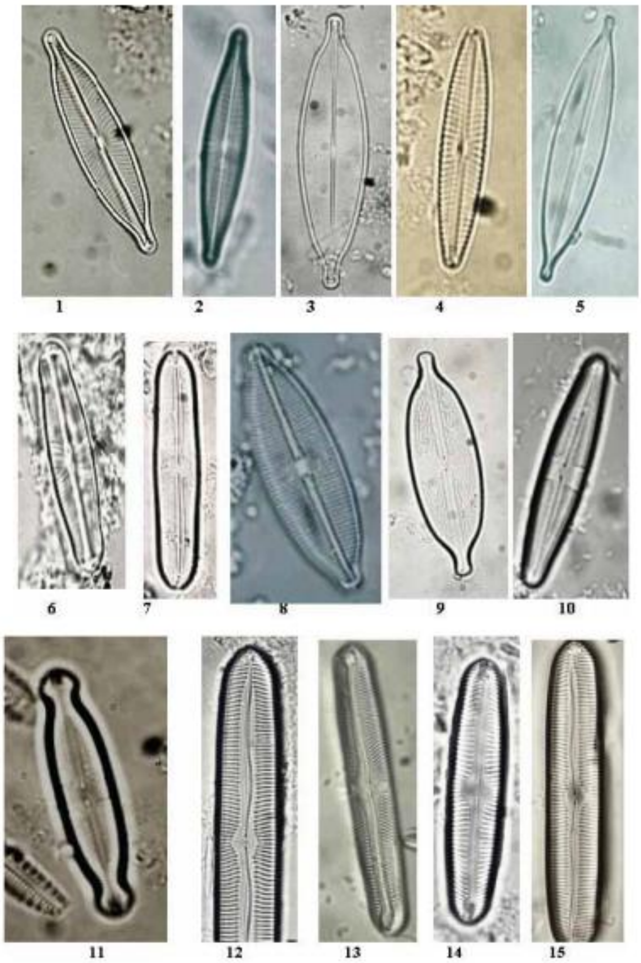

Plate IV: 1-*Navicula cryptocephala (1200X), 2- Navicula cryptocephala var, veneta (1200X), 3- Navicula cuspidate (1200X), 4- Navicula heufleri var. leptocephala (1200X). 5- Navicula halophila tenuirostris (1200X), 6- Navicula pupula (1200X), 7- Neidium bisculatum var. subundulatum (1200X), 8- Nedium dubium (1200X), 9- Anomoeonies sphaerophora (1200X), 10- Stauraneis obnuse (1200X), 11- Pinnularia interrupta f. minutissima (1200X), 12- Pinnularia major (100X) 13. Pinnularia microstauron (1200X), 14- Pinnularia subsolaris (1200X), 15. Pinnularia viridis (1200X).*

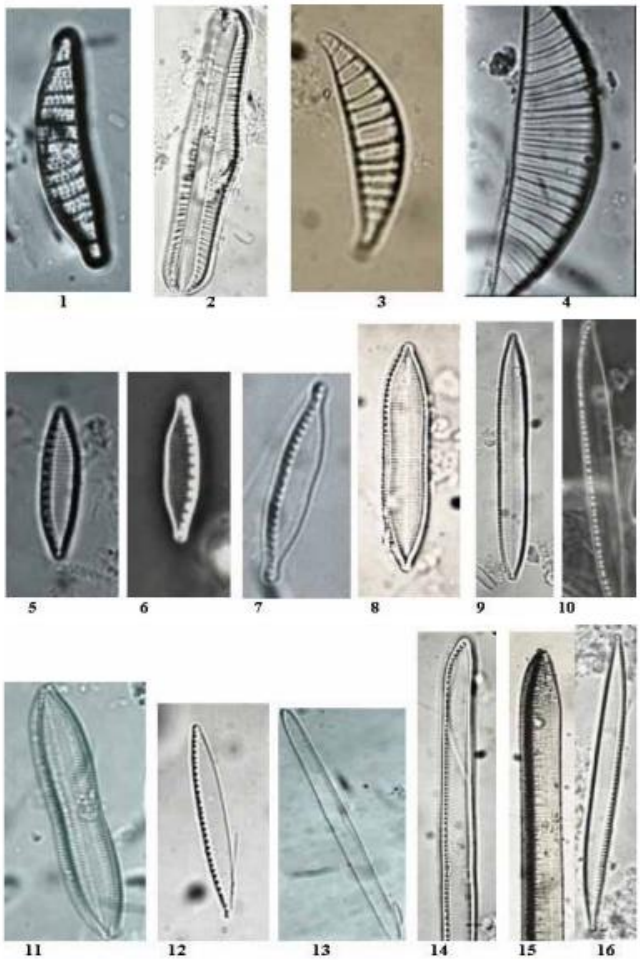

Plate V: *1- Epithemia turgida (1200X), 2- Rhopalodia gibba (1200X), 3- Rhopalodia gibberulla (1200X). 4- Rhopalodia musculus (1200X), 5- Nitzschia amphibian (1500X), 6 Nitzschia elegantula (1500X). 7. Nitzschia microcephala (1500X). 8. Nitzschia apiculata (1500X). 9 Nitzschia constricta (1500X), 10- Nitzschia filiformis (1500X), 11- Nitzschia hungarica (1500X), 12- Nitzschia palea (1500X), 13- Nitzschia obtuse (1500X), 14- Nitzschia obtusa var. kurzii (1200X), 15- Nitzschia scalaris (1200X). 16- Nitzschia sigma (1500X).*

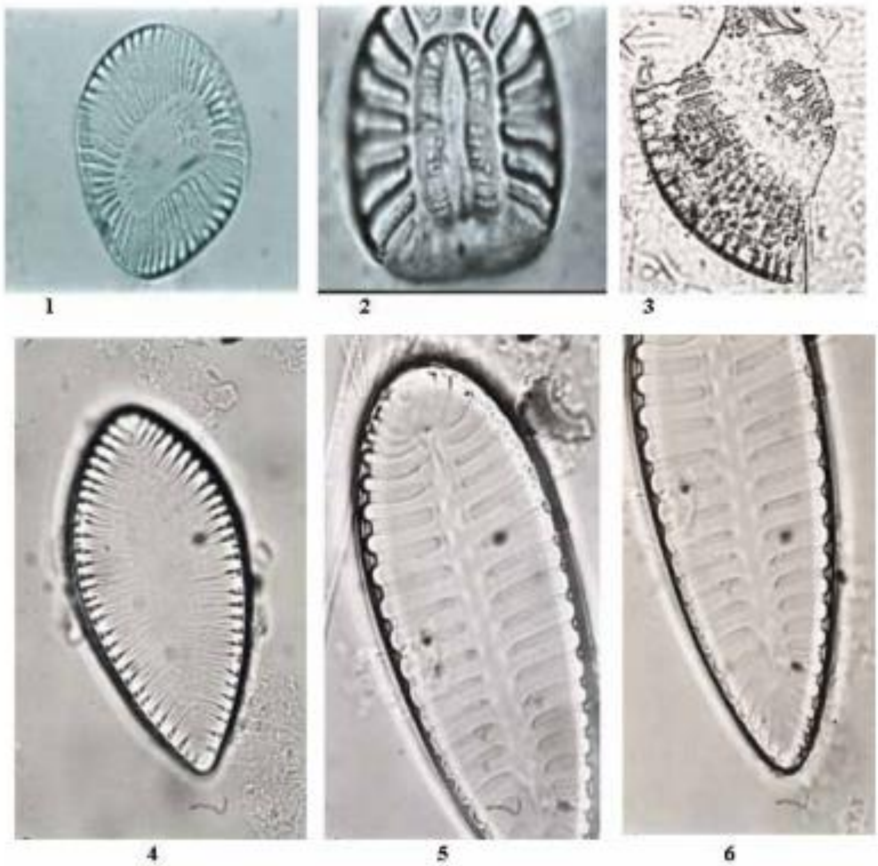

Plate VI: *1. Campylodiscus clypeus (1000X), 2. Campylodiscus clypeus var. bicostata (1000X), 3.Campylodiscus echeneis (1000X), 4- Surirella ovalis (1100X). 5, 6- Surirella elegans (1100X)*. The photomicrographs by A.F.Hamed. Copyright reserved

3-DISTRIBUTION AND ECOLOGY

There is a tonne of material on the geographic and environmental dispersion of diatoms. Many floral studies and lists detailing the locations and environmental factors that enable diatoms to flourish have been created almost since the beginning. Even in a shortened form, this treatment cannot possibly cover all of this material. There are several top-notch references that might help to synthesis the vast amount of data on this area of diatom research. Publications by (**Kolbe, 1932; Patrick, 1948; Cholnoky, 1968**) are especially helpful. Moisture and light are necessary elements for diatom growth. Depending on the temperature and chemistry of their surroundings, they can be found all over the world in all latitudes, from the deepest ocean depths to the highest mountain peaks. Their environment can be divided into two main categories: habitats in freshwater and the ocean. Freshwater diatoms and marine genera and species are often kept apart, and members of one group are not typically found in the habitat of the other. Nonetheless, some diatoms can be found thriving in environments that aren't purely marine or freshwater in nature, like estuaries, tidal pools, and backwaters. There are several organisms that can survive in both fresh and brackish water as well as the ocean. Several organisms may survive in both fresh and brackish water. However there is usually a distinct separation between marine and freshwater organisms, both in terms of the group as a whole and in terms of specific species. Planktonic marine diatoms including *Chaetoceros, Biddulphia, Thallasiosira*, *Coscinodiscus, Ditylum*, and *Rhizosoleni*a are mostly centric in nature. With the exception of a few central freshwater forms like *Cyclotella, Melosira*, and *Rhizosolenia,* most freshwater plankton diatoms are pennate, such as those seen in *Tabellaria, Asterionella*, *Synedra*, *Fragillaria*, *Nitzschia*, and

Surirella. In actuality, with very few exceptions, discoid diatoms are marine, and both saltwater and freshwater commonly contain bacillar or naviculoid forms. Freshwater and brackish water diatoms' existence it would be necessary to be aware of all limnological aspects. The distribution of diatoms must be understood in the context of all existing chemical and physical conditions, processes, and interactions. The plankton diatoms are divided by **Patrick and Reimer (1975)** into small forms called nanoplankton and larger forms called net plankton. *Cyclotella glomerata*, *Stephanodiscus hantzschii*, and *C. comta* are a few types of nanoplankton. *Rhizosolenia*, *Synedra*, and *Asterionella*, among other taxa, are representative of the net plankton, which is frequently organised into colonies or is relatively vast in size. Diatoms dwelling on the substrate in shallow or deep water are known as benthic or bottom forms. The majority of these organisms are represented by raphe-shaped forms. Specific examples include members of the genera *Campylodiscus*, *Navicula*, *Nitzschia*, *Pleurosigma*, and *Surirella*. Epiphytic forms are those that develop in close association with other substrata, such as submerged aquatic plants or decomposing organic matter. As is frequently the case with *Cymbella* and *Gomphonema* species, they may be linked by gelatinous stalks or stipes, or they may be more sessile-like, as is the case with the genera *Achnanthes* and *Cocconeis*. In addition to *Nitzschia* sp., several *Frustulia* and *Eunotia* species have also been shown to frequently reside in the tops of sphagnum plants (endophytically). Ponds, pools, reservoirs, bogs, swamps, and backwaters are among the most frequent types of quiet water habitats. These ecosystems all provide temporary or permanent support for diatom flora of one form or another. If they are not dried out too quickly, some diatoms may withstand prolonged desiccation. In pools, ditches, and other places where water may evaporate and then replace itself, the diatoms quickly come back to life and reappear. A distribution of floating, neritic, and benthic forms may emerge in reasonably large pools or ponds, especially those with substantial depth, and is remarkably similar to the distributions found in lakes. In reservoirs, diatoms can be found on the walls and other built-in elements that are submerged in water. Some of these diatoms can cause issues with the water supply, such as taste and odour, corrosion of the concrete, and clogging of the filters. Given the chemical, physical, and biological characteristics of bogs and swamps, diatoms there are typically represented by rather distinctive flora. For diatoms, rivers and streams offer a habitat where the water is moving, at least to some extent. Most rivers and streams have a range of water movement, including sections towards the center where the water moves quite quickly and areas near the banks where the water moves relatively slowly and/or pools. Several forms of diatom appearances are influenced by the water's flow rate. For example, planktonic diatoms are hindered in relatively rapid water, and slime forms are unable to proliferate under such circumstances. The diatoms that adhere themselves to their substrate via mucus in stalks or masses are the most successful in swiftly moving streams. Among the examples given by **Patrick and Reimer (1975)** are *Achnanthes*, *Cocconeis*, *Cymbella*, and *Gomphonema*. They also suggest that the speed of the river may have an impact on the morphologies of the diatoms. As an illustration, desmogonium is long with hardly capitate ends in swiftly moving waters, while it is short with broad capitate ends in calm waters. River plankton is typically found near the banks in eddies and pools and around the borders of streams or in the streambed when the current is greatly diminished. While streams lacking slower water sections typically do not support plankton diatoms to the same extent, large rivers typically have well-developed plankton populations in regions of slower water movement, such as the estuary. *Asterionella, Cyclotella*, Diatom, *Fragilari*a, *Melosira*, *Nitzschia*, *Synedra*, and *Stephanodiscus* are the primary genera of plankton found in large rivers, according to **Patrick and Reimer (1975)**. In the United States, *Melosira*, *Cyclotella*, *Stephanodiscus*, *Fragilaria*, *Tabellaria*, and *Synedra* are found most frequently. Habitats diatom populations are also supported by springs (including hot springs) and waterfalls, sometimes directly on rocks that are submerged in the bubbling or rushing water and other times on substrates that only receive splashed and sprayed water. The latter situation is also common along rivers and streams, where erratic flows sputter pebbles, stones, or soil onto isles and/or banks. The spring that generates a pool, in the opinion of **Patrick and Reimer (1975)**, is a far better diatom habitat than the spring that forms a cascade. They also point out that *Odontidium heimale* var. *mesodon* is particularly adapted to such habitats. Although a variety of diatoms can survive in hot springs between 70 and 80 degrees Celsius and thrive there, the typical flora of hot springs consists of eurythermal diatoms (ones that withstand a rather wide range of temperatures). It has been discovered that the flora of hot springs in the Dutch East Indies is identical to that of 45°C flowing water. Many diatoms are found in environments where water is not always submerged and may only be provided by spray, rain, snow, condensation, dew, seepages, and other periodic and non-constant sources. This type of habitats includes mosses, tree trunks, damp rocks and stones, caverns, leaves, and soil. Diatoms living in the habitats mentioned above and those that can resist the rigours of drastically different water conditions may be categorised as aerophilous forms. *Pinnularia borealis*, *Melosira roesena*, *Navicula fragilarioides*, and *N. confervaceae*, as well as specific species of *Cymbella*, *Gomphonema*, *Synedra*, *Achnanthes*, and *Cystopleura*, are among the diatoms that Patrick and Reimer claim can be found on rocks or moss that is maintained moist by leaking springs. (VanLandingham does not advise using the later genus name). It is advised to include the majority of diatoms previously identified as *Cystopleura* species in the genera *Epithemia* and *Rhopalodia.* Diatoms are more prevalent in the top centimetre of soil and are less common in woodlands soil than in field or garden soil. The more prevalent soil species include *Hantzschia amphioxys*, *Navicula atomus*, *N. nitrophila*, *N. mutica*, N. *contenta* f. *biceps*, *Pinnularia habifouriana*, *P. brebissonii*, and *P.*

borealis. **Krasske (1929)** observed protococcus, *Eunotia fallax* var. *gracillima*, *Melosira Dickiei*, *Navicula contenta*, *N. Krasskei*, and *N. sohrensis* coexisting on dry rocks, according to **Patrick and Reimer (1975)**. Several extremely little kinds of dry moss are present. Included are *Navicula contenta* var. *parallela* and var. *elliptica*, *Navicula mutica* var. *cohnii* instead of *Navicula mutica*, and smaller versions of *Navicula fragilarioides*, *Pinnularia borealis*, and *Melosira roeseana* instead of its lengthy filamentous variations.

3.1 DIATOM DISTRIBUTION: CHEMICAL AND PHYSICAL FACTORS

Substances including calcium, iron, silicon, nitrogen, sulphur, copper, and chromium are crucial for diatom dispersal. Some of them prevent the growth of specific species, while others are necessary for all diatom growth. One of the most significant chemical parameters determining the distribution and occurrence of diatoms is the hydrogen-ion concentration (pH). In fact, it is so significant that a number of researchers have been able to classify diatoms according to the pH ranges of the waters in which they are found. Diatom distribution and occurrence are also greatly influenced by the influences of light, temperature, and turbulence. There are countless combinations of chemical and physical elements that could interact to affect the growth of diatoms. Diatom spectra are collections of each diatom species' physical, chemical, and biological tolerances. When these spectra are compared to species diversity, they can reveal information about the ecology of a group of diatoms. The distribution of these groupings serves as an illustration of the different physical and chemical components thought to be significant. **(Hustedt, 1937 – 39)**. pH ranges 1.Acidobiontic forms, which can be found at pH values lower than 7, reach their peak development at pH values below 5.5. 2. Acidophilous forms, which are best when the pH is below 7, are present at roughly a pH of 7. 3. Indifferent forms, which start to develop at pH 7. 4. Alkaliphilous forms—also present at a pH of about 7, but with an ideal pH exceeding 7. 5. Alkalibiontic forms, which can only be found in alkaline water. **Existing spectrum (Hustedt, 1937 - 39)** 1. Limnobiontic forms, which are most common in still water 2. Limnophilous forms—whose development is best in lentic water. 3. Variable forms—common in both lotic and still water 4. Rheophilous creatures, which flourish in flowing water. 5. Rheobiontic forms—they are particularly associated with running water. **Spectrum of Halobin (Kolbe, 1927**) 1. Oligohalobous forms, which are mostly common in fresh water (water with less than 5% salt content), are a. Halophobous forms are almost salt-averse and are most common in water that lacks chloride. b. Indifferent forms - appropriate freshwater forms. c. Halophilous forms, which are primarily found in freshwater but can also survive in slightly brackish water. 2. Mesohalobous forms, or brackish water forms, are most prevalent in water with a salt content of 5–20%. 3. Euhalobous forms, or true marine forms, flourish best in water that contains 30–40% salt**. Scale Saprobic (**Collingsworth *et al.*, 1967 in **McLaughlin, 2012**) 1. A polysaprobic zone is one that has little to no oxygen and is typical of a decomposing area. Zone A of the mesoprobic ecosystem, which is rich in amino acids and an oxidative zone. Zone B is the zone of final recovery and terminal oxidation. 3. The pure water zone is oligosaprobic. 4. The pristine water zone of the katharobic. **Spectrum of Habitat** 1. Plankton forms are typically present in the plankton. 2. Benthic and epilithic forms, which are those that are affixed to or live on rocks or the seafloor. 3. Epiphytic forms, which cling to other plants without developing parasitically on them. Depending on their characteristics, diatoms in this spectrum may be classified as euplankton (belonging to the real plankton), tychoplankton (living a portion of their life on the bottom), or littoral (being found in the littoral zone). **Spectrum of nutrients** 1. Eutrophic forms are those that are oxygen-depleted throughout the summer and are found in relatively shallow lakes and ponds that are rich in organic matter and nutrients. 2. Oligotrophic forms - present in deep lakes with continuously oxygenated water and low levels of organic matter production relative to water volume. 3. Dystrophic forms are seen in lakes with low levels of calcium carbonate, large levels of humus, and very low levels of nutrients (**McLaughlin, 2012**).

3.2. GEOGRAPHIC DISTRIBUTION

In general, diatoms can be found wherever there is water, hence they might be said to be cosmopolitan. Additionally, it is true that a large number of diatom genera and species are somewhat global in their occurrence. When considering the distribution of diatoms, it is impossible to separate geographic and environmental elements. The living circumstances present at that specific area are the reason why diatoms flourish there. Yet, despite the fact that many places of the planet have environments that are conducive or even optimal for some species of diatoms to thrive, these environments do not contain these species. Of fact, the methods used to move diatoms from one place to another have an impact on their dispersion globally. Winds, ocean currents, geological phenomena, birds, animals, and man himself with his various ways of movement may all disperse diatoms. Any attempt to describe the global distribution of diatoms must be exceedingly cursory because so little is known about what species actually occur in some parts of the earth. The information that follows must be viewed in that context. Certain genera, species, and groups of forms are found in particular deposits, nations, or materials, while others appear to prevail there. There may be reasonably typical assemblages in different parts of the same nation. This is especially true in nations with diverse temperatures and/or topographic features. The United States contains humid (forest), subhumid (grassland), semiarid (steppe), and arid (desert) regions, which affects the differences in the diatom flora in the eastern, central, and western regions of the nation. Contrarily, there are similarities between the flora of the eastern United States and that of Western Europe, New Zealand and that of Great Britain, as well as Campeachy Bay and the Phillipines. The endemic genera and species appear to vary throughout South America according to the region studied for similar reasons, and there seem to be distinct flora differences between northern and southern Africa. Very conclusive comparisons cannot be established due to the paucity of data on diatom floras in many regions of the world. Nonetheless, the student can learn a lot about specific topics by reading the literature. For instance, central Europe, which includes Germany, France, Holland, Switzerland, Austria, Hungary, and Belgium, has received a lot of attention. There is also a presence from Great Britain and northern European nations like Sweden and Finland. The book by Patrick and Reimer on the United States looks to be a very useful resource, and new, significant books are also coming out on the diatoms of the USSR and Southern Africa.

Diatoms from various biotopes around Egypt were the subject of extensive biodiversity research projects (**Foged, 1980; Shaaban, 1994; El-Awamri *et al.*, 1996; Hamed, 2008; Shanab, 2006; Mansour *et al.*, 2015; Khairy *et al.*, 2017; El-Sheekh *et al.*, 2018**; and the references cited in). Species identification of the above mentioned literatures was based on light microscopy. Besides the interest in their spatio-temporal distribution and ecological niches, algal- and diatom-based environmental assessment (**El-Naghy *et al.*, 2006; El-Sheekh *et al.*, 2010; Shaaban *et al.*, 2012; Abd El-Karim, 2014; Yusuf *et al.*, 2018**) and paleoenvironmental reconstructions (**Zalat, 2003**) have also been pursued in some studies. In 1994, Shaaban published a detailed list of 912 freshwater species and infraspecies of cyanoprokaryotes and algae, along with information on their ecological status and geographic distribution in Egypt's ecologically diverse inland waters. This was done as part of an assessment of

Egypt's biological diversity. In 2008, Hamed, compiled the diversity and distribution of blue-green algae, and also diatoms, in some Egyptian inland water biotopes with respect to conductivity, and recorded 353 different species and infraspecies. He emphasized the difficulty in segregation of bluegreen algae into marine and freshwater species but provided a diatom-based ecological characterization. The previous works by **Shaaban (1994), Hamed (2008), Saleh (2009)**, and other researches are among the most trustworthy taxonomic sources accessible as a help for the identification of Egyptian diatoms with regard to diatoms. More intriguingly, in recent years, integrative studies have described some algal and diatom species from various biomes that were new records for Egypt or even new to science, and it is anticipated that more endemic and cryptic species will be discovered in the future, especially in isolated arid-land freshwater ecosystems with fewer human influences (**Cantonati *et al.*, 2020**). *Aulacoseira ambigua* f. *japonica* its curved forms were discovered for the first time in Egypt in the River Nile basin, and this discovery also marked the second record for the entire African continent (**Janse van Vuuren *et al.*, 2018**). The new epilithic amphoroid diatom species *Seminavis aegyptiaca* has also been found from the Damietta Branch estuary of the River Nile as part of the ongoing PhyBiO investigation on the variety and distribution of the Egyptian algal flora (**Saber *et al.*, 2020**). The freshwater diatoms *Cyclostephanos invisitatus*, *Encyonema neomesianum*, and *Gomphonema laticollum* have only rarely been documented in the previous Egyptian studies, according to **Saber *et al.* (2021)**, who identified them from sampling locations in the northern part of the Damietta Branch of the River Nile, Egypt.

4- FORMATION OF DIATOMITE

Diatomite creation takes a long time and involves four steps: The primary focus of the first stage is on the diatom cell's capacity to generate siliceous frustules in an ambient environment. By sophisticated biomineralization processes, diatoms produce their frustules. The Golgi apparatus, microtubules, and a model of other protein nanostructured matrices are thought to play a role in the species-specific process by which the living cells take silicic acid up from the environment, convert it into silica nanospheres, and then arrange them to form various parts of the frustule (**Gröger *et al.*, 2016; Kotzsch *et al.*, 2015; Kröger, 2007**). The ability of the diatom to reach a high enough cell concentration to enter the blooming state, or the expansion of living cells, which necessitates the availability of nutrients (eutrophication) as well as other environmental conditions, is the second step (**Shaw *et al.*, 2003**). The deposition of dead diatom remnants, whole frustules, or its fragments is a component of the third phase. The siliceous frustules that settle at the bottom (benthos) create a very fine layer of sediments that typically include other elements. If sedimentation occurs in the ocean one diatom frustule or one valve at a time, it is too slowly (**Alldredge & Gotschalk, 1989**). Nonetheless, there are processes that shorten the time diatom remnants spend settling. The primary mechanism involves grazing zooplankton feeding on living diatoms, which leads to the creation of faecal pellets that contain frustule fragments. The diatom remnants' sedimentation is accelerated by the faecal pellets (**Liu & Wu, 2016**). Another method involves the variation of physicochemical properties during, for example, seasonal shifts, notably in temperate, arctic, and coastal locations, which occurs without the absorption of living cells by grazers. This mechanism might involve the blooms flocculating and the protoplasts rapidly disintegrating (**Alldredge & Gotschalk, 1989**). Once the living diatom cells die, they begin to coagulate with other detritus, bacteria, etc. to create larger coagulated particles that sink more quickly (**O'Brien *et al.*, 2002**). When phytoplankton cells become more sticky, the flocculation process takes place. In addition to various physicochemical aspects of the environment, bacteria, and the effective size of algal cells, other factors include the algae's physiological and morphological stickiness. The number of bacteria linked to bloom cells increases quickly when the bloom transitions into its decreasing phase, which can increase the stickiness of the aggregated phytoplankton cells and even include mucus secretion (**O'Brien *et al.*, 2002**). The final process takes place over a longer period of time, during which time diatom frustules build up layer by layer, getting thicker. These sedimentary layers undergo diagenesis processes and become diatomite (**Wallace *et al.*, 2006**).

4.1 Structure, attributes, and optimization of diatom silica

Diatom silica, a naturally occurring biomaterial made from single-celled algae, is regarded as an important usable biomaterial for energy storage and conversion. Diatoms' distinctive forms and structured porous structures at the micro- and nanoscale levels, which exhibit high specific surface area, thermal stability, and affordability, provide tremendous benefits and prospects for application in place of synthetic materials. Yet, in the last 20 years, there has been a lot of research into the creation of novel approaches for the production and storage of energy using synthetic materials with nanoscale dimensions and special features. It has drawbacks and bad effects (**Schlapbach & Zuttel, 2001; Arico *et al.*, 2005**). Issues are listed, including high manufacturing costs, lengthy batch production times, a lack of scalability, the use of hazardous chemicals, and the creation of hazardous waste, all of which are incompatible with existing climate protection requirements (**Cerneaux *et al.*, 2007; Biswas & Wu, 2005**). One of the most impressive examples of biologically derived nanostructured materials is the amorphous silica exoskeletons (frustules) of single-celled diatoms (**Makar *et al.*, 2015**). The estimated 100,000 different species of diatoms each have a characteristic 3-D silica shell called a frustule, which is ornamented with a special arrangement of nano-sized features like pores, ridges, spikes, and spines (**Mann, 1999; De Stefano & De Stefano, 2005; Losic *et al.*, 2009; Makar *et al.*, 2015**). Recently, the term "diatom nanotechnology" was coined to characterise the burgeoning subject that explores these remarkable materials and their uses in a variety of fields, including molecular biology, materials science, biotechnology, nanotechnology, and photonic (**Losic *et al.*, 2009**). Numerous potential uses for diatom silica have been suggested and investigated, including those in optics, photonics, catalysis, biosensors, drug delivery, microfluidics, molecular separation, filtration, adsorption, bioencapsulations, and immunoisolations, as well as template synthesis of nanomaterials. (**Yu *et al.*, 2010; Bao *et al.*, 2011; Yu *et al.*, 2011**). Diatom frustules and pore structures are equivalent in size on the micro- and nano-scales to light wavelengths, which enhances their optical scattering capabilities and allows them to be employed as photoelectric devices (**Zhang *et al.*, 2008; Jeffryes *et al.*, 2008; Noll *et al.*, 2002; Anderson *et al.*, 2000**). Due to its high resistivity, diatom silica has limits when it comes to energy conversion and storage. The modification or conversion of silica into other materials while preserving the diatom structure is the subject of extensive research. Many materials, including metals, semiconductors, carbon, and polymers, were modified. (**Losic *et al.*, 2009**). Several techniques based on metal (Au, Ag, Pt) and nanoparticle coatings, using hydrothermal conversion, sol-gel chemical vapour deposition, and atomic layer deposition have been presented to convert silica surface into composite materials with new and more effective optical, electrical, and magnetic properties (**Losic *et al.*, 2009**). Diatoms were conformally coated with ZnFe2 O4/SiO2 using a hydrothermal process in conjunction with thermal annealing. Due to the 4G-6S transition in Mn2+ ions, these coatings displayed green photoluminescence (**Ernst *et al.*, 2007; Weatherspoon *et al.*, 2005**). Moreover, conformal coating of diatoms by different oxides has been made possible by sol-gel surface-coating techniques working in conjunction with structure-directing agents (**Ernst *et al.*, 2007; Liu *et al.*, 2007**). Using the atomic-layer deposition of titania, it was also demonstrated that shrinking the size of diatom-membrane holes while maintaining their form produced photocatalytically active diatom silica (**Losic *et al.*, 2006**).

5- DIATOM NANOTECHNOLOGY

Long ago, material scientists learned about the special qualities and uses of manufactured porous materials, such as porous silica (**Davis, 2002**). Porous silica's application potential is influenced by the size, shape, and distribution pattern of its pores as well as the size and form of its particles. Numerous varieties of macro, meso, and microporous silica were very helpful in nanotechnology applications because they provided materials with a very high surface area and fascinating chemical and physical properties (**Yao *et al.*, 2017; Slowing *et al.*, 2007; Giraldo *et al.*, 2007; Li *et al.*, 2012; Tsai *et al.*, 2000**). Diatoms naturally produce porous silica with a range of particle sizes, shapes, and distributions, including macro- and mesoporous silica. Diatoms have repeating structures and holes that can be as large as 1 micron across and as small as mesoporous scale (> 50 nm) (**Willis *et al.*, 2010**). Moreover, diatom porous silica has been reported as a potential material for nanotechnology due to its pores size (**Gordon *et al.*, 2009; Jeffryes *et al.*, 2011;Mischler *et al.*, 2014**). Regarding the vast majority of undiscovered diatom species, these microorganisms can offer us a huge catalogue of various pore sizes, shapes, and other parts and structures that will make it simpler to choose from the species that are already available or try to genetically or environmentally modify their morphogenesis to produce the desired design. These facts increased the usefulness of diatom frustules and contributed to the emergence of the "Diatom Nanotechnology" field (**Crawford *et al.*, 2001; Gordon and Parkinson, 2005; Losic, 2017**). Diatom nanotechnology is a brand-new area of multidisciplinary study that involves partnerships between scientists and engineers in the fields of biology, biochemistry, biotechnology, physics, and material science. It focuses on the use of diatoms or their mechanisms for forming silica to create nanodevices (**Gordon *et al.*, 2009; Losic, 2017**). Diatom frustules have the ability to construct intriguing 3D silica structures with finely inherited nano-details, which makes them useful in nanotechnology (**Townley *et al.*, 2008; Gordon, 2010**). There are two popular methods for diatom nanotechnology: bionanotechnology, which directly utilises living organisms or their constituent parts (**Goodsell, 2004; Guo, 2005; Gazit, 2007; Reisner, 2008**) and biomimetic, in which we attempt to duplicate or improve upon what we believe organisms are doing (**Dickerson *et al.*, 2008; Gebeshuber *et al.*, 2009**). Although there are currently no diatom-based products on the market, numerous working applications have been described in the literature, and further devices have been conceptualised in patents and patent applications. Diatom frustules have been identified in multiple investigations as an active component in drug delivery systems, sensors (**Dolatabadi and de la Guardia, 2011**), solar cells, batteries, electroluminescent devices (**Jefrrey *et al.*, 2011**), lab-on-a-chip, templates, and lab on a chip (LoC) devices. Moreover, certain species were described as being natural slabs of photonic crystal containing waveguides (**Mischler *et al.*, 2014**).

6- INDUSTRIAL APPLICATIONS OF DIATOMS

6.1. Diatoms for Lithium Ion Battery Materials

A popular anode material for lithium-ion batteries, silicon has a high capacity of 4200 mAh g1. (**Poizot *et al.*, 2001; Etacheri *et al.*, 2011**). In the past, a variety of silicon materials, such as silicon films, nanoparticles, electrochemically generated porous silicon, etc., were investigated for use in Li battery applications (**Poizot *et al.*, 2001; Etacheri *et al.*, 2011**). The ability to facilitate the quick transport of lithium ions due to its highly accessible surface area for liquid electrolytes providing excellent rate properties and maintaining good electronic conductivity during charging/discharging cycles was found to be one of them. This porous silicon had a unique hierarchical structure and high surface area. The development of electrodes with novel porous nanoarchitectures that can significantly boost performance by reducing crystal strain and increasing the surface area accessible for ion transport is crucial to improving the performances of porous silicon electrodes. Silica's performance as an anode material is substantially hampered by severe volume expansion and rapid capacity fading during the lithium-ion insertion and extraction operations, which results in the pulverisation of the electrode structure and poor cycling performance.(**Losic *et al.*; 2007**). It is important to increase the surface area and porosity of the silicon anode by including new nanoscale morphologies, such as nanowires, nanotubes (**Gordon & Drum, 1994**), nanosheets, and nanospheres (**Lewin, 1990**). The generated Li ion batteries' discharge capacity performance was measured utilising a variety of silicon architectures, including 3D porous Si particles (approximately 2600 mAh g1), Si nanotube arrays (about 1800 mAh g1), and Si nanotubes (about 1000 mAh g1) (**Campbell *et al.*, 2016**). One of the first demonstrations of carbon coated and converted diatom silicon as a High Rate Capable Li-ion Battery Anode was presented by Campbell et al. in recent work (**Campbell *et al.*, 2016**). Diatom silicon was made by carbonising with polyacrylic acid (PAA) after being reduced from diatom silica using a magnesiothermic technique. In contrast to the DE's original BET specific surface area of 7.3 cm2 g1, the subsequent diatom-converted nano-Si displayed a high BET specific surface area of 162.6 cm2 g1. SiO_2 structures seen in DE are perfect bio-derived templates for silicon nanoscaled.

6.2. Diatoms for Energy Storage: Supercapacitors

Zhang team came up with the idea of using diatomite's 3D structure in conjunction with manganese and Ni oxides to create composite electrodes for the use of electrochemical capacitors, demonstrating the significant potential of these innovations (**Zhang *et al.*, 2014; Guo *et al.*, 2016; Li *et al.*, 2015; Wen *et al.*, 2016**). On the purified diatomite, MnO_2-modified nanosheets are seen to grow vertically, increasing the specific surface area of the electrode and creating hierarchical architecture.

6.3. Diatoms for Solar Cells

The development of dye-sensitized nanocrystal solar cells (DSSC), such as TiO_2-diatom lattices used in the production of such solar cells by increasing the specific surface area of diatoms, enabling dye molecules deposition onto the nonstructured surfaces of diatoms (**Pan *et al.*, 2004; Schlapbach & Zuttel, 2001; Toster *et al.*, 2013**). According to **Fuhrmann *et al.* (2004)**, diatom has a refractive index of 1.43, whereas porous TiO2 thin films have refractive indices that range from 1.7 to 2.5 (**Tachibana *et al.*, 2007**). This results in TiO2-diatom layers having a high dielectric layer contrast and light scattering in the pore array. In other words, the TiO2-diatom molecule has increased the DSSC's effectiveness (**Huang *et al.*, 2015**).

6.4. Diatoms for Hydrogen Storage

Diatomite (diatomaceous earth) is a mineral that is ideal for storing hydrogen because of its high porosity, large surface area, small particle size, great adsorbability, and exceptional thermal stability (**Karatepe *et al.*, 2004**). The inherent pore features of diatomite substantially influence the hydrogen adsorption capability. Recently, researchers looked into an efficient metal-modified technique for dispersing Pd and Pt nanoparticles on diatomite. Hydrogen adsorption capabilities are increased to 0.696 wt% and 0.980 wt%, respectively, by integration with 0.5 wt% of Pt and Pd. Hence, diatomite mineral is the promising physisorption-based material for hydrogen storage at room temperature due to its wide surface area, suitable pore volume, and small pore size.

6.5. Diatoms for Thermal Energy Storage

Diatomite is a potential candidate for use in phase change materials for thermal energy storage since it is lightweight, affordable, and cheap (**Jeong *et al.*, 2013**). Due to its evident benefits of high energy storage density and limited temperature variation during the thermal energy charge/discharge process, phase change material (PCM) is the most efficient approach (**Regin *et al.*, 2008;**

Memon, 2014; Zhou *et al.*, 2012). Diatoms and PCMs have been combined for the past 20 years as a possible method for reducing energy consumptions, such as Hexadecane/diatomite has a melting point of 23.68 degrees centigrade and a latent heat of roughly 120 j/g, whereas paraffin/diatomite composite has a melting point of 41.11 degrees centigrade and 70.51 j/g.

6.6. Diatoms for Water Treatment

Diatomite, an eco-environmental functional material, has been shown to be a very promising and effective adsorbent in the treatment of heavy metal-contaminated water because of its high porosity, low density, high specific surface area, and surface silanol groups. Amorphous silica makes up the majority of it, with just trace amounts of carbonates and organic stuff (**Gao *et al.*, 2005; Du *et al.*, 2014; Gomez *et al.*, 2014**). The unique integration of physical and chemical properties, such as high porosity with 80–90% voids, chemical inertness, low thermal conductivity, and a combination of small pore sizes and large specific surface area, is the main cause of its high absorption capacity in water treatment (**Bakr, 2010; Mendonça *et al.*, 2011; Zhao *et al.*, 2014**). Its distinct applications are also a result of the different structure and pore network. In comparison to low turbid water, diatomite coagulates effectively at high turbidity greater than 100 NTU (reduction efficiency > 90%) (cited in **Raj *et al.*, 2018**). In order to effectively remove various contaminants from drinking water, such as heavy metals like Pb2+, Cu2+, Cd2+, Zn2+, and Cr+3, natural and modified DE can be utilized (**Khraisheh *et al.*, 2004; Caliskan *et al.*, 2011; Du *et al.*, 2013; Dobor *et al.*, 2015; Du *et al.*, 2015**), organic dyes (**Khraisheh *et al.*, 2005; Li *et al.*, 2014, Mohamed *et al.*, 2019**), and using depth filtering techniques, it is possible to remove some types of viruses and hazard microbes (**Michen *et al.*, 2012**). The cleaning up of oil spills and petroleum compounds including benzene, toluene, ethyl-benzene, xylenes, and methyl tertiary butyl ether from aqueous solutions has also been accomplished with success using DE (**Aivalioti *et al.*, 2010; Aivalioti *et al.*, 2012**). Additionally, natural diatomite may be utilized in conjunction with artificial polymer like polyaluminum chloride (PAC), polyferric sulphate (PFS), and polyacrylamide for extensive filtering directly in the substantial water stations to start a coagulation-flocculation step in which suspended particles like clay, viruses, algae, and other organic or inorganic pollutants will flocculate at the bottom or on the surface, making their removal by bottom or surface collection easy (**Zhao *et al.*, 2014**).

6.7. Diatomite for Thermal Insulation

Diatomaceous earth might make a fantastic substitute when making building bricks with excellent thermal insulating qualities. Diatomite has already been used as insulating layers for thermal insulation and heat preservation of thermal furnaces in metallurgical plants, power stations and heat transmission (**Saran, 2012**). Diatomite can be used to create coating layers for pipes or other surfaces to provide effective thermal protection (**Wenhua & Faai, 2007**). **Ye *et al.* (2017)** found that applying DE in tandem with two other thermal insulating fillers might reduce the thermal efficiency of a multi-thermal acrylic coating with a water base. In addition, **Martinez (2014)** also created a unique coating using diatomite that can withstand corrosion and fires.

6.8. Diatomaceous Earth as a Filler

Diatomaceous earth has been utilised as a filler in the paper industry and the rubber industry, particularly for tyres, in both its raw and/or modified forms. (**Giannini & Nahmias, 2007**), in asphalt, the ceramic industry, pharmaceuticals (**Mikulásik & Albrecht, 2013**), in feeding e.g. poultry (**Liu & Fowler, 2016**), paints (**Gysau, 2006**), plastics e.g. polypropylene pipes (**Zhao *et al.*, 2018**), and dental material (**Lu *et al.*, 2012**). In order to improve the physical qualities of sheets and achieve light-weight printing papers, modified diatomite was utilised as an active filler in the paper industry (**Shang *et al.*, 2018**). It was also used for flame retardancy and smoke suppression (**Jin-bao *et al.*, 2008**). After being modified appropriately, diatomite is utilised in the rubber industry as a semireinforcing filler to raise the elastic modulus of the rubber (**Lamastra *et al.*, 2017**). Additionally, diatomite has been proposed as a candidate for an active filler in various types of asphalt (i.e., asphalt is a mixture consisting of asphalt, aggregates, and inert or active mineral filler), used to enhance the asphalt's antistripping, antiaging (**Cheng *et al.*, 2018; Shukry *et al.*, 2018; Yang *et al.*, 2018**), and a number of mechanical properties including those concerning anti-deformation. Using titania/diatomite composite as an antibacterial filler in ceramics and paints used in bathrooms and watering holes (**Cheng *et al.*, 2018**). Recently, improved eco-friendly films for food packaging were made using diatomite as a bolstering filler in conjunction with poly (lactic acid) and extract made from grinding coffee (**Cacciotti *et al.*, 2018**).

6.9. Diatomaceous Earth as Abrasive Material

Calcined DE has been added to toothpaste to increase its ability to polish away the spots on teeth from coffee and tea (**Yeh & Synodis, 1986**). Moreover, it can be used to clean the surfaces of metals, particularly metallic stainless (**Gordon, 1971**), and thermoplastic polymers that are employed to make eyeglass lenses (**Liu, 2010**). Moreover, it has been added to dishwashing solutions as a component for improved cleaning procedures (**Chirash *et al.*, 1988**).

6.10. Diatomaceous Earth as a soil amendment

DE could improve the physical structure of the soil, assist the soil retain water for longer periods of time in spite of sandy soil, and aid in the removal of heavy metals and hydrocarbons from contaminated regions (**Aksakal *et al.*, 2013; Angin *et al.*, 2011**), as well as boosting the amount of leaves, tillers, and panicles in rice as well as the plant's capacity to withstand various conditions including the presence of heavy metals, aridity, or salinity (**Abdalla, 2011a; b**). There are many businesses that sell DE for soil amendment on the market. Diatomaceous earth comes in a range of particle sizes, from very fine powder to big blocks. While huge bricks are only appropriate for preserving soil moisture, using highly refined powder possibly more useful after incorporating into a growth medium or soil to maintain good performance in all the aforementioned purposes.

6.11. Diatomaceous Earth-Based Pharmaceutical and Biomedical Applications

Diatoms, with their distinctive 3D silica structures made under hospitable and natural settings, serve as models for the creation of a new generation of biomaterials whose properties are quite similar to those of synthetic porous silica materials. Diatom frustules have been used as a novel, inexpensive scaffold for a variety of biomedical applications because of their distinctive hierarchical porous structure, high surface area, tailorable surface modification, high biocompatibility, chemical stability, and specific optical and photoluminescence properties**.** Mesoporous silica has recently demonstrated promising results in drug delivery systems because of its special chemical and physical characteristics, including large surface area, excellent capacity for medication loading and biocompatibility. Diatomite has been proposed as an alternative natural source due to its high surface area, good ability to control its surface chemistry through functionalization processes, and excellent biocompatibility. These advantages outweigh the disadvantages associated with the use of mesoporous silicon created artificially, such as the high cost, toxicity of the materials, and high energy involved in the synthesis (**Aw *et al.*, 2013; Terracciano *et al.* 2016**). It was the first time that novel chitosan - diatomite composite membranes had been created (**Tamburaci & Tihminlioglu, 2017**), and the results were very encouraging. These membranes had improved surface areas, swelling properties, surface roughness, and protein adsorption capacities—all of which are crucial for osteoblast adhesion and proliferation.

Acknowledgement

I am grateful to Dr. Hesham Abd El-Fatah, assistant professor of Phycology in the Botany department, Faculty of Science, Ain Shams University, for his invaluable assistance and cooperation in finalizing the article for publication.

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