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Advanced materials for water capture applications to enhance water supply: A systematic review

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Abstract— ***The demand for clean and renewable water sources continues to increase as water scarcity increases. This review explores the potential of advanced materials that add to water harvesting and treatment processes to reduce impending dangers. This review starts with assessing traditional water harvesting methods, spring development, fog collection, and desalination. The AWG system operates in three main steps: air is drawn in by solar-powered fans and filtered, water vapor is absorbed by special materials, and then solar heat converts the vapor into pure water. A mineral cartridge enriches the water with calcium and magnesium for better taste, and a large tank stores the water for future use. Sorbent materials like MOFs, silica gel, and zeolites play a key role by capturing atmospheric moisture until heated to release water all their strengths and weaknesses. This article describes newly emerging nanomaterials such as zero-valent iron nanoparticles, carbon nanotubes, and photocatalysts with increased contaminant removal and energy efficiency. Bioinspired materials from nature, such as desert spider silk and beetles, are described for innovative water harvesting. Finally, the overview compares membrane-based technologies such as reverse osmosis and membrane bioreactors according to their significance in modern-day water purification systems. By integrating recent advancements and identifying core challenges, the present review presents a broader view of how the evolution of sustainable, efficient, and scalable water treatment technologies is promoted by the use of advanced materials.***

In conclusion, the ability of AWH to supply SMDW (safely managed drinking water) to a billion people was demonstrated. Using Google Earth Engine 13, the evaluation presents a fictitious 1-meter-square device with a (specific yield) SY profile of 0.2 to 2.5 liters per kilowatt-hour (0.1 to 1.25 liters per kilowatt-hour for a 2-meter-square device) for 30% to 90% relative humidity. An average person's daily drinking water needs of five liters might be satisfied by such a device.

Keywords— ***Advanced materials, Membranes, Water supply, Water harvesting***

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I. INTRODUCTION

The increase in global water demand together with the scarcity of potable or fresh water calls for the development of innovative technologies for water capture and supply. Desalination, wastewater treatment, and rainwater harvesting, among other traditional methods, have limits in terms of cost, efficiency, and environmental impact. Recently, advances in materials science have led to the emergence of advanced materials with special properties that can increase water capture efficiency, reduce energy consumption, and promote sustainability.

Water is needed for economic development, human survival, and environmental sustainability. The significance of water capture and supply cannot be overstated, as water capture plays a critical role in human health, economic development, food security, environmental sustainability, climate change mitigation, energy production, and operational stability. Water capture and supply play a critical role in climate change mitigation, as they help reduce greenhouse gas emissions from energy production, industry, and agriculture. The significance of water capture and supply is further emphasized by the following statistics: 4.2 billion people lack access to safe sanitation [1], 2.1 billion people lack access to safe drinking water [1], water scarcity affects 40% of the global population [2], and the global water demand is projected to increase by

55% by 2050 [3]. To meet the demand for fresh water, a focus has been placed on water resources such as seawater and water vapor, which are not readily available; however, a focus has been placed on freshwater and seawater to meet this freshwater demand. Thus, technologies that collect water from the atmosphere or oceans have been created. It has shown promise as a remedy for water scarcity in recent decades [4]. Owing to the diverse water sources and forms on Earth, harvesting is often possible.

Research on water harvesting technology has advanced significantly during the past century. A prominent source of inspiration for water harvesting system design is nature. Desert beetles can collect water in arid deserts because of their alternating hydrophilic bumps and hydrophobic surfaces on their backs [5]. Water can be directed to the roots of cacti, a plant known for its vitality in deserts, owing to the unique aligned structures of its spines, barbs, and trichomes [6][7].

This review aims to provide a comprehensive overview of advanced materials for water capture applications, focusing on their properties, synthesis methods, and potential applications. This review provides a comprehensive examination of the current state of the art, challenges, and future directions in the development and implementation of advanced materials for water capture applications. By highlighting the latest breakthroughs and trends in this field, this review aims to stimulate further research and innovation, ultimately driving the development of sustainable water capture solutions that address the global water crisis.

In conclusion, water capture and supply are critical for human health, food security, economic development, environmental sustainability, energy production, social stability, and climate change mitigation. Prioritizing water supply and capture is crucial to ensuring a sustainable future for everybody. Ninety-five (96) studies that were retrieved from the Google Scholar, PubMed, Web of Science, and EMBASE databases were included in the review. The selected articles were published between 2001 and 2025 and employed a combination of qualitative and quantitative methods. The sample (S), the phenomenon of interest, design (D), evaluation (E), and research type (R) were the predefined criteria for article inclusion for screening. The articles that met the selection criteria were screened using the SPIDER framework and the PRISMA-P standards.

This article begins by examining conventional methods of water harvesting, including spring development, fog harvesting, and desalination. The AWG system functions in three key stages: solar-powered fans draw in and purify air, absorbent material captures the water vapor, and solar heat condenses the vapor to yield clean water.

II. TRADITIONAL WATER CAPTURE METHODS

Traditional water capture methods have been used for centuries to collect, store, and distribute water for various purposes. These methods are often simple, low-cost, and adaptable to local conditions. Some traditional water capture methods include the following:

A. Fog collection

Mesh or mesh-like materials are used to capture fog droplets, which are then channelled into a storage system for use as drinking water or for irrigation. A widespread natural occurrence, fog is characterized as a cloud composed of numerous water droplets near the ground, with widths usually ranging from 1 to 30 µm, lowering visibility to less than one kilometer [8]. Numerous processes, including the advection of moist water across water bodies, can result in the formation of fog [8]. Although fog water may contain marine dust or salt, it should meet freshwater standards after treatment. Because oceans have high water content, fog can easily form near coastlines, especially when it is combined with mountainous areas. Figure 1 shows these coastal locations with many fog days to enact fog harvesting technology [9].

Thus, it has been suggested that harvesting water from fog is a practical way to alleviate water scarcity, particularly in regions where fog is common but rainfall is limited, as demonstrated by the fog harvesting initiatives completed in Chile. The air at ground level may contain suspended water droplets with diameters ranging from 1 to 50 µm, which are commonly referred to as fog, depending on the relevant circumstances [10].

These hanging water droplets build together to produce a mass of humid air, which might constitute a major supply of freshwater, especially in arid areas. To collect the fog, a vertical mesh is utilized to block the droplet stream, also called the moist air stream, which results in the collision and coalescence of the suspended water droplets. The water then enters a collection gutter, a storage tank, or a distribution system [11]. Fog collectors made of vertical mesh can be developed using a variety of screen materials, including alloy nets, plexiglass, plastic, and aluminium [12]. The topography and geography of possible fog harvesting locations must support dense fog, particularly in arid regions with intermittent rainfall; this may include a high mountain range near a coastline and, for best fog interception, perpendicular to the wind [13][14], [15].

[16] reviewed data on how plants and animals obtain atmospheric water in a hyper-arid environment with very little rainfall. They proposed that tilted surfaces with alternating hydrophobic, wax-coated, and hydrophilic, nonwaxy regions could be used to collect fog [17]. The wings of Namib Desert beetles, which accumulate fog water in the early morning, have this type of surface. However, more recent laboratory studies have demonstrated that a beetle's fog-basking behavior is crucial for capturing water from fog than the surface structural characteristics of its wings [18]. [16] reported that more studies of eco-physiological mechanisms could enhance the use of fog- and dew-water capture techniques and called for research into low-cost techniques that extract water from unsaturated air via osmotic pressure or incredibly fine hydrophilic structures connected to pumps [19]. Nevertheless, existing freshwater resources—such as lakes, rivers, and groundwater—are becoming insufficient to meet increasing demand because of environmental deterioration and human-caused pollution [20].

B. Spring development

Identifying and developing natural springs as a source of water, often involve the construction of collection systems, storage tanks, and distribution networks. Since ancient times, researchers have utilized straightforward and reasonably priced methods for collecting water from springs [21]. People who live in impoverished or rural mountain villages are mainly worried about the growth of springs because they can easily and affordably obtain clean water from nearby sources [22]. Ensuring that the spring flow rate is consistent throughout the year is crucial when considering its use as a water supply. The flow rate should be monitored throughout the year, but it is especially important to do so in the late summer and fall when the groundwater level is at its lowest. Because surface runoff that seeps into the ground may contaminate springs, water quality is also a crucial factor to consider [23].

Concentrated springs are clearly and frequently observed along hillsides where groundwater is driven through cracked bedrock; these springs are generally not as contaminated as other types of springs and are relatively easy to develop, as shown in Figure 2. Concentrated springs usually occur when groundwater originates from one defined discharge at the Earth's surface [24].

In lowland or valley regions, several concentrated springs can be found. It can be particularly challenging to protect a spring from bacterial contamination because surface water tends to flow toward these valleys [25]. Because of this, water gathered from these locations must be tested frequently and, if needed, disinfected. The procedures outlined above for the construction of a concentrated spring can be used to create a lowland spring; however, a collecting wall might not be required [24].

The purpose of spring development is to take running water underground to shield it from surface contamination and deposit it in a sanitary spring box. Whether the spring is a seepage spring or a concentrated spring, determine a proper development, which helps protect the water supply from being contaminated [26]. Seepage springs are places where groundwater "seeps" from the soil across wide distances. The method of creating seepage springs involves diverting groundwater to a collection location after interrupting its flow over a large subterranean area. Seepage springs are more challenging to safeguard against surface water contamination than are concentrated springs because they gather water over a wider region [27]. The most challenging process is seepage spring development. They are readily contaminated by groundwater from sources that may be relatively near the surface and spread over a large area. To meet their water needs, local communities in some parts of the region create seepage springs via traditional methods [28]. Seepage springs typically do not have enough water to flow past their aboveground location because of inadequate permeability, which can either release water or not because of low porosity [29]. By creating caverns of the right size, the discharge of the seepage spring can be improved by expanding the seepage surface. These developed seepage springs have very low average flow rates, but building a spring water collection box guarantees a sufficient water supply [30].

If locally accessible materials are employed, spring development costs are modest, and gravity flow water delivery systems make tap water for distribution affordable. The created spring offers a year-round supply of safe drinking water to nearby residents, animals, and wildlife. Seepage springs and seeps form based on site characteristics, including the height of the seepage face relative to the surrounding region, as shown in Figure 3. As demonstrated below, spring can be generated in a variety of ways [31].

There is no hard-and-fast rule regarding how seepage springs or seeps should emerge; instead, it depends on the site [32].

People who live in mountainous areas have used spring water for generations as their primary source of domestic water, but in recent years, its discharge has been gradually decreasing, and the majority of it has dried. Local towns are currently facing a severe domestic water crisis as a result of this circumstance, forcing them to travel great distances to obtain fresh water from downstream sources [33].

Despite these annoyances, one of the most important or alternative ways to provide fresh water to nearby towns is the construction and management of seepage springs. Although the seepage spring has a relatively slow rate of discharge, effective management of these small water sources will provide a supply of water during the year's dry spells [34]. The implementation of various seepage spring development strategies, such as spring box construction, cave excavation, seepage areas, and water collection structures at seepage faces, will sustain local communities and stakeholders throughout the year. Proper spring development also helps to preserve the water from contamination [31]. The type and depth of the soil, steep slopes, rainfall characteristics, and other factors may limit the options for using traditional water harvesting techniques. For this reason, it is crucial to create an appropriate plan for managing water resources [35].

C. Desalination

As the world's population increases and supplies of high-quality freshwater resources dwindle, the application of desalination technologies has spread, especially in areas where other water supplies or traditional treatments are either economically unfeasible or environmentally unsustainable [36]. Desalination is a collection of processes in which excess salts and minerals are extracted from water. These processes generally treat seawater or brackish water and produce two different outputs, lower dissolved salt and mineral content freshwater, which is a saline byproduct of high salt concentration, commonly referred to as brine, with a greater salt concentration than the original feed water. The feed water for desalination can be from either brackish water or seawater—the latter having salinity between that of freshwater and seawater [37].

As of 2016, there were more than 18,426 operational desalination facilities around the world that collectively produced over 86.8 million cubic meters of water per day. The facilities are spread across close to 150 nations and provide desalinated water to more than 300 million individuals, substituting or complementing their daily water intake in the process [38].

Desalination is achieved primarily by two significant technological processes: thermal distillation and membrane filtration. Both are utilized in municipal, industrial, and commercial applications. Desalination has also become more affordable as a consequence of technological advancements, making it a beneficial process for meeting growing demands for water [39]. Additionally, desalination plants powered by renewable sources are available, especially in off-grid or distant locations. Since water obtained through desalination techniques is typically free of natural minerals, remineralization would have to be undertaken so that the water thus obtained may be made suitable for consumption. Disposal of highly concentrated brine byproducts should also be performed with environmental care [40].

Desalination has numerous benefits. It uses a very abundant resource—seawater—and enables drinking water to be made in water-scarce coastal areas. In addition, the range of available technologies makes it possible to tailor the desalination process to local prevailing conditions [41]. Nonetheless, the process is not without faults. Desalination plants are bound to be connected with high capital costs and energy demands. The resulting brine is of environmental concern in the case of poor handling, whereas the treated water needs posttreatment to add minerals for it to be appropriate for drinking [42].

III. NANOMATERIALS FOR WATER CAPTURE

Improved water and wastewater technologies can be developed by combining cutting-edge nanotechnology with traditional process engineering [35]. Three methods of using nanotechnology to clean contaminated water and wastewater include the adsorption of contaminants on nanoparticles (NPs), the catalytic annihilation of pollutants by nanoparticles, and the process of nanoscale filtration [36]. Numerous nanomaterials have been created for water and wastewater filtration, including graphene, metallic nanoparticles, graphene oxide (GO), carbon nanotubes, polymer nanomaterials, graphene, graphene, and (nano) zeolites [37].

Novel nanoparticles enabled by nanotechnology can be used to remove viruses, toxic metal ions, metal oxides, and organic and inorganic solutes from wastewater, surface water, groundwater, and other natural materials. These techniques include reverse osmosis, carbon nanotubes, nanofiltration, nanofiber filters, and ultrafiltration membranes [43]. Figure 4 depicts four types of nanoscale materials that are thought to be useful for filtering water: dendrimers, carbonaceous nanomaterials, metal-containing nanoparticles, and zeolites. These materials are appealing as separation and reactive materials for water filtration because of their varied physiochemical characteristics [44].

The high surface-to-volume ratios of nanomaterials enable them to interact effectively with bacteria and pollutants [41]. Some of the treatments that are now in use are improved by nanotechnology. Nanomaterials, which are materials with large surface areas and dramatically changed properties, usually have diameters of less than 100 nm [45]. This has led to the creation of tremendous opportunities for water treatment and sustainability via nanotechnology [46].

Nanotechnology could be used to avoid contaminating water and other natural resources, as well as to conserve water and associated nonrenewable energy sources. Additionally, this tactic might be used to protect biodiversity, ecosystems, and habitats so that future generations can meet their requirements. Owing to growing public awareness of environmental issues, the use of hazardous chemicals and solvents has increased to the point where it is no longer feasible to proceed without implementing an environmentally friendly plan [47]. Advanced nanomaterials for the treatment of groundwater, surface water, wastewater, and other ecological materials containing hazardous metal ions, metal oxides, organic and inorganic solutes, and microorganisms are promoted by nanotechnology. These approaches include ultrafiltration membranes, reverse osmosis, nanofiltration, carbon nanotubes and nanofiber filters. Large-scale cleaning sites have used a variety of Nano remediation techniques, such as nano zero-valent iron, for groundwater cleanup [48].

A. Nanoparticle-based catalytic moist air oxidation

While designing highly selective nanotechnology catalysts that have the right mix of metal atoms and other dynamic components is difficult, the real benefit of using organic functional polymers for nanocatalyst manufacturing is how simple it is to alter the composition of the polymer to create a customized catalyst [46]. These catalysts have outstanding activity, stability, and selectivity. The production of platinum, palladium, and ruthenium nanoparticles contained in a highly cross-linked polystyrene matrix as effective catalysts for the CWAO of phenol is described in this study. The use of platinum nanoparticle-coated hypercrosslinked polystyrene to treat phenol compounds with CWAO results in high phenol conversion [47].

Catalytic moist air oxidation of $C_2H_2O_4$ employing Pt catalysts in a bubble column reactor provides an efficient technique of burning at a very low temperature in contrast to thermal incineration [48]. Catalytic wet air oxidation (CWAO) has recently attracted significant attention because of its comprehensive and extremely effective solution against industrial wastewater, which can quickly oxidize hazardous contaminants into products of no concern (CO_2, H_2O, and N_2). Carefully chosen catalysts enable this.

B. Nanoscale zero-valent iron

There are several useful types of nanoparticulate zero-valent iron for the reduction and elimination of nitrates from sediments, soils, and water. They have been utilized to alter and detoxify polychlorinated biphenyls and organochlorine herbicides [49]. These nanoparticles have been shown to change into less hazardous byproducts when dissolved in water. Examples of organic pollutants include nitro aromatics, chlorinated benzenes, chlorinated alkenes and alkanes, and organic colors.

The application of iron nanoparticles in Nano-remediation offers numerous advantages. Iron (II) and iron (III) are converted to iron at the nanoscale via the use of borohydride as a reductant. The zero-valent iron nanoparticles are 10 to 100 nm in diameter and feature a typical core and exterior. While zero-valent or metallic iron makes up the majority of the center, metallic iron oxidation produces a mixed valent [Fe^{+3} and Fe^{+2}] oxide layer. Owing to its enormous surface area, several reactive sites, and dual adsorption and reduction capabilities, nanoscale zero-valent iron is a popular choice for Nano-control [50].

The most researched nanotechnological environmental method for groundwater purification is nanoscale zero-valent iron (nZVI). Many common pollutants, including chlorinated ethenes, pesticides, dyes, brominated and trihalomethane, chlorinated methane, chlorinated benzenes, and other polychlorinated hydrocarbons, have been demonstrated to be very effectively eliminated by metallic iron at the nanoscale. The process is catalyzed by the corrosion of zero-valent iron in the environment.

$$2Fe^0 + 4H^+ + O_2 \rightarrow 2Fe^{2+} + 2H_2O$$
$$Fe^0 + 2H_2O \rightarrow Fe^{2+} + H_2 + 2OH^-$$

In addition to organic contaminants, nZVI can also reduce inorganic anions such as chromate perchlorate, selenite, nitrate, arsenite, and arsenate. Its sorption capacity is noticeably higher, and its reaction rates are many times faster than those of conventional granular iron. Additionally, nZVI can remove dissolved metals such as Pb and Ni from solutions by reducing them to lower oxidation states or making them zerovalent [49]. Sodium borohydride is commonly used as the major reductant to produce nZVI. For example, $FeCl_3 \cdot 6H_2O$ (0.05 M) and $NaBH_4$ (0.2 M) solutions are mixed (1:1 volume ratio). When borohydride reduces ferric iron, the following occurs [50].

$$4Fe^{3+} + 3BH_4^- + 9H_2O \rightarrow 4Fe^0 \downarrow + 3H_2BO_3^- + 12H^+ + 6H_2$$

For many years, granular ZVI reactive barriers have been employed in many locations worldwide to filter out both organic and inorganic pollutants from groundwater. Since this technology is often less hazardous to the environment than other removal methods are, nZVI has been a popular choice in recent years [51]. The characterization, synthesis, and use of nanoscale Fe0 particles and Fe^0/Ni^0, Fe^0/Co^0, Fe^0/Ag^0, Fe^0/Pd^0, and Fe^0/Pt^0 in ecological remediation have been summarized by [52]. The development of nanoscale zero-valent iron (Fe^0) and bimetallic Fe^0 particles as effective redox media has enabled the detoxification of inorganic and organic contaminants in aqueous solutions, and bimetallic Fe^0 nanoparticles have successfully transformed redox-active metal ions such as chromium(VI) into less dangerous and mobile chromium(III) species. These nanoparticles can convert inorganic anions (such as nitrates) and a variety of organic contaminants (such as chlorinated benzenes, pesticides, organic dyes, nitroaromatic compounds, alkanes and alkenes, and PCBs) into less hazardous and resistant byproducts in aqueous solutions [53].

C. Photocatalysis

The main problem preventing water treatment from being as effective as it could be and eliminating waterborne viruses without producing harmful disinfection byproducts is the removal of nonbiodegradable organic contaminants that are not impacted by traditional treatment methods. To solve these problems, a creative, economical, and ecologically friendly method that can remove these pollutants with little energy and chemical consumption must be developed. Research has therefore focused on AOPs as trustworthy, alternative processes that have the potential to oxidize and mineralize a variety of organic molecules [54]. AOPs produce highly strong and aggressively oxidizing radicals. Photocatalysis is a well-known AOP that can be utilized to increase the biodegradability of persistent organic pollutants and remove both novel and emerging microbial diseases. Light, chemical, or other energy sources can activate a catalyst used in a class of processes known as photocatalytic oxidation [55]. This type of oxidation relies on the production of strong reactive radical species, such as H_2O_2, $O_2{\bullet}^-$, O_3, and hydroxyl radicals (OH•), which are strong, nonselective oxidizing agents [55].

Heterogeneous photocatalysis is an effective water purification approach for sterilizing water and reducing persistent organic pollutants (see Table 1).

Carbon nitride, chalcogenide nanosheets, graphene, and metal oxides are among the 2DM-based photocatalysts that have recently been investigated for various uses. 2DM-based photocatalysts fall into three categories on the basis of the type of pollutant: inorganic contaminant removal, biological disinfection, and organic decontamination. Other efficient catalyst systems, such as electrocatalysts, have been developed for water treatment; recent topical studies provide more details.

IV. BIOINSPIRED MATERIALS FOR WATER CAPTURE

Scientists have discovered that numerous animals in nature, including the Namib desert beetle, which lives in desert environments, can successfully trap tiny droplets in the air to survive [56]. With alternating patterns of hydrophobic shells and hydrophilic bumps, creatures have a unique wettable structure and morphology that enables them to absorb moisture from fog-containing air to meet their daily survival demands. Nature served as inspiration for the development of bioinspired materials, which quickly gained popularity [57]. According to earlier research, a range of design and preparation techniques for bioinspired water collection materials have been created by mimicking the micro/nanostructure, morphology, and wettability of creatures such as cacti, spider silk, and desert beetles [58]. The most effective method for creating high-efficiency bioinspired water collection surfaces is to investigate and mimic the water collection mechanisms of various creatures. However, a major issue limiting their development is sustainability. The current surface of the water catchment is incredibly brittle and unsuitable for severe climates. The safety of the collected water must also be assessed because of the prolonged humidness of the atmosphere. Thus, ways to increase the service life and safety performance of water collection surfaces are essential [59][60].

The most effective method for creating high-efficiency bioinspired water collection surfaces is to investigate and mimic the water collection mechanisms of various creatures. However, a major issue limiting their development is sustainability. The current surface of the water catchment is incredibly brittle and unsuitable for severe climates. The safety of the collected water must also be assessed because of the prolonged humidness of the atmosphere. Thus, ways to increase the service life and safety performance of water collection surfaces are essential [61].

Overview of some of the animals that can collect fog and several techniques that use biomimicry and bioinspiration to help collect water from fog.

A. Namib Desert beetles

Beetles called *Stenocara gracilipes* and *Onymacris unguicularis* are indigenous to southern Africa's Namib Desert, one of the driest places on earth, with an average annual rainfall of just 1.8 cm. It is not unusual to have years in a row with no rainfall at all [62]. However, there is life in the area; several plant and animal species appear to flourish. The accumulation of water from fog was thought to be the cause of the ability of this area to survive in this climate. Even though there is little rainfall, fog is created along the coast 60–200 days a year by the predominant southwesterly winds, which can blow up to 50 km inland [63]. In the Namib Desert, fog harvesting was first observed in 1976 when beetles emerged during nocturnal fog events and lowered their heads while facing the wind (Figure 5) [64]. The water seeped into the mouth of the beetle from its body. Weighing the beetle both before and after fog harvesting revealed that harvesting could result in an increase of more than 30% in total body weight.

The fog gathering method was discovered in 2001. [65]. A random array of bumps with a diameter of 0.5 mm and a spacing of 0.5 to 1.5 mm was found to make up the beetle's back. The surrounding area contained microstructure wax, but the bumps were smooth. On the bumps, water from the fog begins to fall, and droplets start to form. The droplet continues to expand (up to 4–5 mm) until the weight of the droplet overcomes the capillary force, the droplet detaches and rolls down the tilted beetle's back. [66]. According to this hypothesis, the background wax is hydrophobic (fearful of water), whereas the bumps are hydrophilic. The researchers constructed a model surface using 0.6 mm glass beads glued in wax to verify that the fog harvesting is, in fact, caused by an array of hydrophilic bumps on a hydrophobic background. It was discovered that this surface gathered more water than did the glass or wax surfaces alone [66].

There have been attempts to design fog collectors by imitating beetle strips. Using a mask and plasma deposition, hydrophilic polymers have been applied to a superhydrophobic polymer substrate. Investigations were conducted on the pattern proportions as well as the wettability of the hydrophilic patches. It was discovered that water droplets could not enlarge to a size that would allow their weight to overcome the surface tension on hydrophilic areas with diameters smaller than 400 μm. However, as this was only studied for a single plasma-deposited polymer, the threshold value might vary depending on the wettability [67].

B. Spider webs

Spider silk is a well-researched material with superior mechanical properties. This natural substance, which is made up of proteins, is stronger and more elastic than many manmade materials [68]. Numerous photos showing a web glistening with dew demonstrate that spider webs are also known to collect water (Figure 5). Dry webs undergo structural reorganization in response to moisture. First, water droplets condense, and the cylindrical silk thread swells because of the hygroscopic nature of the proteins in the silk. Rayleigh instability causes this cylinder to split into smaller drops to reduce its surface area. This creates a structure such as "beads on a string," with a number of knots spaced sporadically along the thread [69]. This rebuilding of the web structure and subsequent water capture is believed to be advantageous for the spider since it not only provides a supply of drinking water but also improves prey capture because the water-swollen knots have better adhesive qualities [69].

The wet-rebuilt web was analyzed by scanning electron microscopy (SEM), which revealed that the interconnecting joints were made of stretched porous nanofibrils parallel to the thread, whereas the knots were made of randomly oriented porous nanofibrils [69]. When water condensed on the wet-rebuilt spider thread, the droplets moved to the knots from the joints. This is believed to be caused by a combination of a Laplace pressure gradient because the joints have a larger radius of curvature than do the larger knots and a surface tension gradient because the knots have a rougher surface because of the randomly orientated nanofibrils [69].

V. ADVANCED MEMBRANE MATERIALS FOR WATER TREATMENT

A series of interrelated problems that affect ecosystems and civilizations are caused by water constraints. Reducing agricultural production and escalating crop failure compromise food security and feed the cycle of hunger and poverty [70]. In addition to water scarcity, water pollution is another major concern facing communities worldwide. Industrial discharge, agricultural runoff, incorrect waste management, and inadequate wastewater treatment lead to the contamination of freshwater sources with harmful pollutants, including heavy metals, pesticides, pathogens, and medicines. Water pollution affects aquatic ecosystems, biodiversity, and the sustainability of water supplies for future generations in addition to endangering human health [70].

Given these difficulties, the use of cutting-edge membrane technologies for water filtration shows promise as a way to combat pollution and water scarcity. Membrane-based water treatment techniques, including membrane bioreactors, reverse osmosis, and nanofiltration, provide effective and economical ways to purge water sources of impurities and create potable water and recovered water for a range of uses [71]. Owing to the special filtration qualities of membranes, such as their ability to remove impurities selectively according to size, charge, and solubility, advanced membrane technologies can efficiently treat a variety of water sources, such as brackish water, surface water, wastewater, and seawater [72]. The adoption of cutting-edge membrane technologies for water purification is crucial for addressing the intricate problems caused by the world water crisis. Membrane-based water treatment technologies are essential for preserving human health and safety, preserving the environment, and furthering global development goals because they increase access to clean and safe water, reduce water pollution, and encourage sustainable water management techniques [73].

A. Reverse osmosis (RO) technology

Modern water treatment relies heavily on reverse osmosis (RO) technology, which provides a very efficient way to purify water by eliminating a variety of impurities. Osmosis, a natural phenomenon in which solvent molecules migrate from an area of lower solute concentration to an area of higher solute concentration, is the fundamental tenet of RO across a semipermeable membrane [74]. However, in reverse osmosis, pollutants are separated from the water by applying pressure to overcome this natural osmotic pressure, which forces water molecules to move from the concentrated solution side (feedwater) to the diluted solution side (permeate).

High-quality drinking water is produced by this procedure, which efficiently eliminates impurities from water sources such as organic compounds, heavy metals, dissolved salts, pathogens, and microplastics. Higher permeability, selectivity, and fouling resistance are the results of recent developments in RO technology, which have also improved membrane materials, system designs, and operational tactics [75]. The most recent RO membranes are made of cutting-edge materials with specific qualities, such as greater surface area, reduced pore diameters, and enhanced surface charge characteristics [75].

By increasing water permeability rates, these improvements enable higher water production while preserving high contaminant rejection rates. Furthermore, novel membrane module designs that optimize fluid dynamics and minimize fouling, such as spiral-wound and hollow-fiber configurations, increase the membrane lifespan and lower maintenance needs. [76]. RO technology has transformed water delivery systems in arid and coastal locations that are experiencing water scarcity, such as the Middle East and North Africa. This is because RO technology makes it possible to desalinate brackish and seawater sources. Countries such as the United Arab Emirates, Qatar, and Saudi Arabia have made significant investments in large-scale RO desalination plants to meet the water demands of their fast-developing urban centers and population. Every day, these facilities generate millions of cubic meters of drinkable water to serve industrial operations, agricultural irrigation, and municipal water supplies [77].

In crowded cities and metropolitan regions, RO technology has been crucial in providing millions of inhabitants with access to safe and clean drinking water. To supplement local water supplies and lessen reliance on depleting freshwater sources, cities such as Singapore, Tokyo, and Los Angeles use RO systems as part of their integrated water management strategy [78]. RO technology is used in conjunction with advanced water recycling and purification processes to treat wastewater and generate high-quality drinking water that fulfills demanding safety regulations. In summary, reverse osmosis technology is an enormous step forward in water treatment, providing a very efficient way to eliminate impurities and create drinking water that is of excellent quality. Continuous improvements in membrane technology and system architecture mean that ROs will remain vital tools for addressing water scarcity, safeguarding public health, and guaranteeing access to sustainable and clean water sources across the globe [77].

B. Membrane bioreactor (MBR) technology

Membrane bioreactor (MBR) technology is a cutting-edge approach to wastewater treatment, offering a highly efficient and effective way to produce high-quality effluent that can be reused or discharged. Unlike traditional wastewater treatment systems, which rely on sedimentation or filtration for solids separation, MBRs use external or submerged membranes to improve effluent quality and process efficiency [79]. Fundamentally, membrane filtration and activated sludge or biological treatment processes are combined in MBR technology to create a hybrid system that incorporates the advantages of both treatment modalities. When microorganisms such as bacteria and fungi are utilized, the biological treatment component of MBRs breaks down organic pollutants, nutrients, and pathogens found in wastewater. These bacteria metabolize organic debris, converting it into biomass, carbon dioxide, and water through biochemical processes, hence reducing the pollutant load in wastewater [80].

In addition, MBR technology provides improved operational stability and process control over conventional treatment techniques. Solids separation membranes provide accurate control over hydraulic retention durations, sludge retention durations, and mixed liquor concentrations in the bioreactor, leading to improved treatment efficacy and decreased effluent quality variability [81]. Furthermore, the continuous filtration process of MBRs reduces the possibility of sludge washout and guarantees steady treatment effectiveness over time [82]. In summary, membrane bioreactor technology is a flexible and effective wastewater treatment method that provides excellent effluent quality, operational flexibility, and sustainability. MBRs continue to be developed as crucial technologies for combating water pollution, encouraging water reuse, and guaranteeing environmental protection and public health due to continuous improvements in membrane materials, system design, and operational techniques. MBRs help communities worldwide have a more resilient and sustainable water future through their many uses and demonstrated advantages [83].

CONCLUSION

This report highlights the looming global problem of water scarcity and examines how future materials—either nanomaterials, bioinspired ideas, or innovative membrane technologies—can revolutionize water harvesting and purification. Traditional technologies such as fog gathering, spring creation, and desalination are still working as low-tech solutions, but their shortcomings underpin the necessity of better technologies. Nanotechnology offers promising avenues through high-efficiency filtration, catalytic oxidation, and adsorption of pollutants, whereas bioinspired materials leverage nature's intelligence to improve water harvesting efficiency in diverse environments. In the same manner, membrane technologies such as reverse osmosis and membrane bioreactors are essential for producing potable water from traditional and nontraditional water sources.

Despite major breakthroughs in material synthesis and system integration, there are still challenges in achieving long-term sustainability, cost-effectiveness, and scalability of these technologies. Future studies need to address optimizing material longevity, minimizing energy usage, and improving green synthesis techniques to make them widely applicable.

In conclusion, the integration of new materials into water capture and purification systems is a game-changing way to improve water security in the future. Continued interdisciplinary research and innovation are imperative for developing sustainable solutions that can meet the growing water demands of our planet and provide clean water.

C. Tables

Table 1: Several key nanoscale materials and structures, their applications, and their properties for purifying water.

Nanomaterials	**Applications**	**Properties**	**Reference**
membrane based on aquaporin biomimetic	Desalination at low pressure	exceptional selectivity, high ion permeability, low mechanical strength, and exceptional water permeability.	[84]
Carbon membranes and nanotubes	Point-of-use, desalination, and highly biodegradable contaminants (antibiotics, medicines)	Reusability, energy efficiency, fouling resistance, sorption efficiency, bactericidal effects, health concerns, production costs, and cleaning capabilities all require improvement.	[85]
Membranes of nanocomposite	Reverse osmosis, also known as micropollutant removal	Enhance mechanical and thermal toughness, permeability, fouling resistance, and hydrophilicity.	[86]
Membrane nanofibers	Water purification, prefiltration, ultrafiltration, filter cartridges, and independent filtration devices	Antibacterial, high porosity, bespoke fit, and great penetration efficiency Potential nanofiber release and pore blockage	[87]
membranes for nanofiltration	decrease in color, hardness, heavy metals, and odor	High selectivity, charge-based repulsion, membrane obstruction (concentration polarization), and comparatively low pressure	[88]
Self-constructing membranes	Ultrafiltration	Laboratory-scale homogenous nanopores, specialized membranes, and trace quantities	[89]
Zero-valent iron nanoparticles	Wastewater treatment and cleanup (perchlorates, chlorinated hydrocarbons)	very reactive; surface changes for stability	[90]
Ag and TiO_2 NPs	Surface antibiofouling, organic compound cleanup, isolated areas, and point-of-use water disinfection	Nanotitanium dioxide is long-lasting, antibacterial, low in toxicity to humans, and requires ultraviolet light to activate.	[91]

Polymeric dendrimers, or nano adsorbents,	Removal of organics and heavy metals	The reusable production process is bifunctional, multistage, and multifunctional (heavy metals are adsorbed by the outside branches, while organics are adsorbed by the interior shell).	[92]
(Nano)zeolites	Disinfection procedures	A regulated release of antibacterial reduced active surface occurs when Nano-silver particles are immobilized.	[93]

D. Figures

Figure 1. Methods for collecting fog water [94].

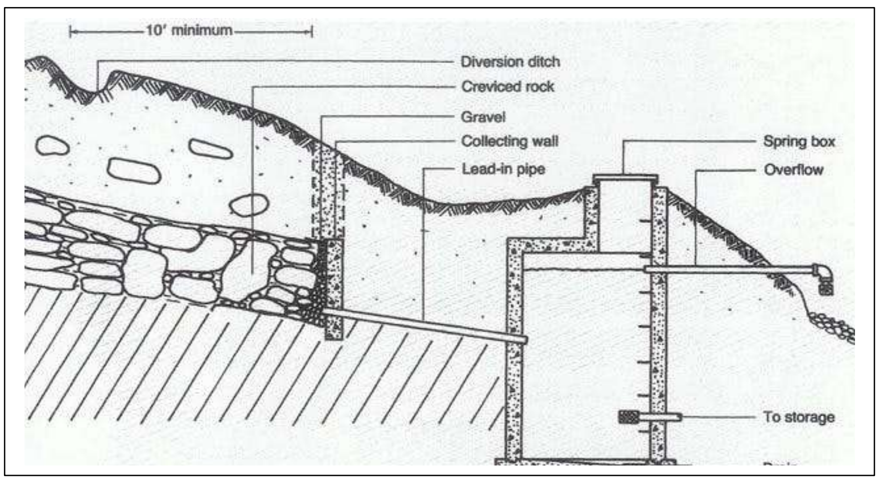

Figure 2. (Adapted from "Safeguarding Wells and Springs Against Bacterial Contamination" from the Department of Agricultural and Biological Engineering at Pennsylvania State University.)

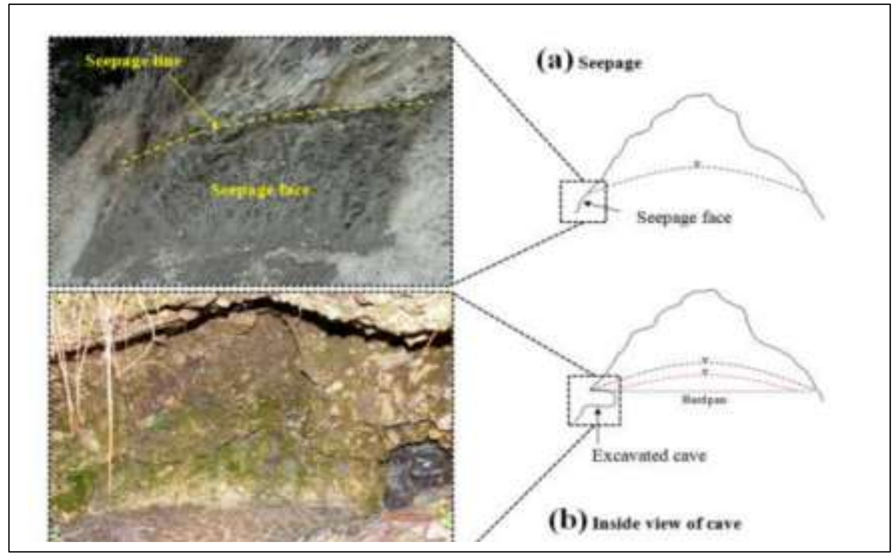

Figure 3. Spring seepage, (a) displays the seepage face and line, (b) displays the cave's interior [32].

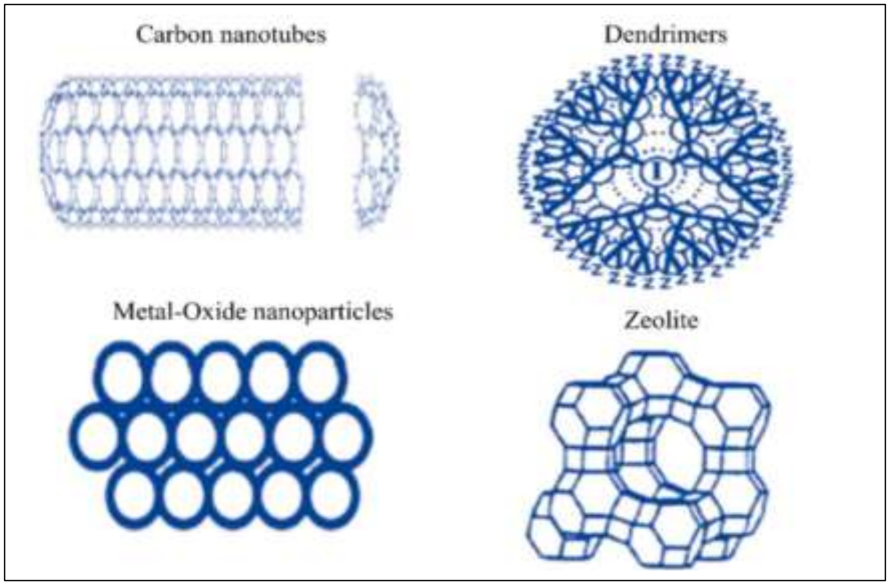

Figure 4. *Shows that a few of the nanoparticles are now under consideration for application as water purification products [95].*

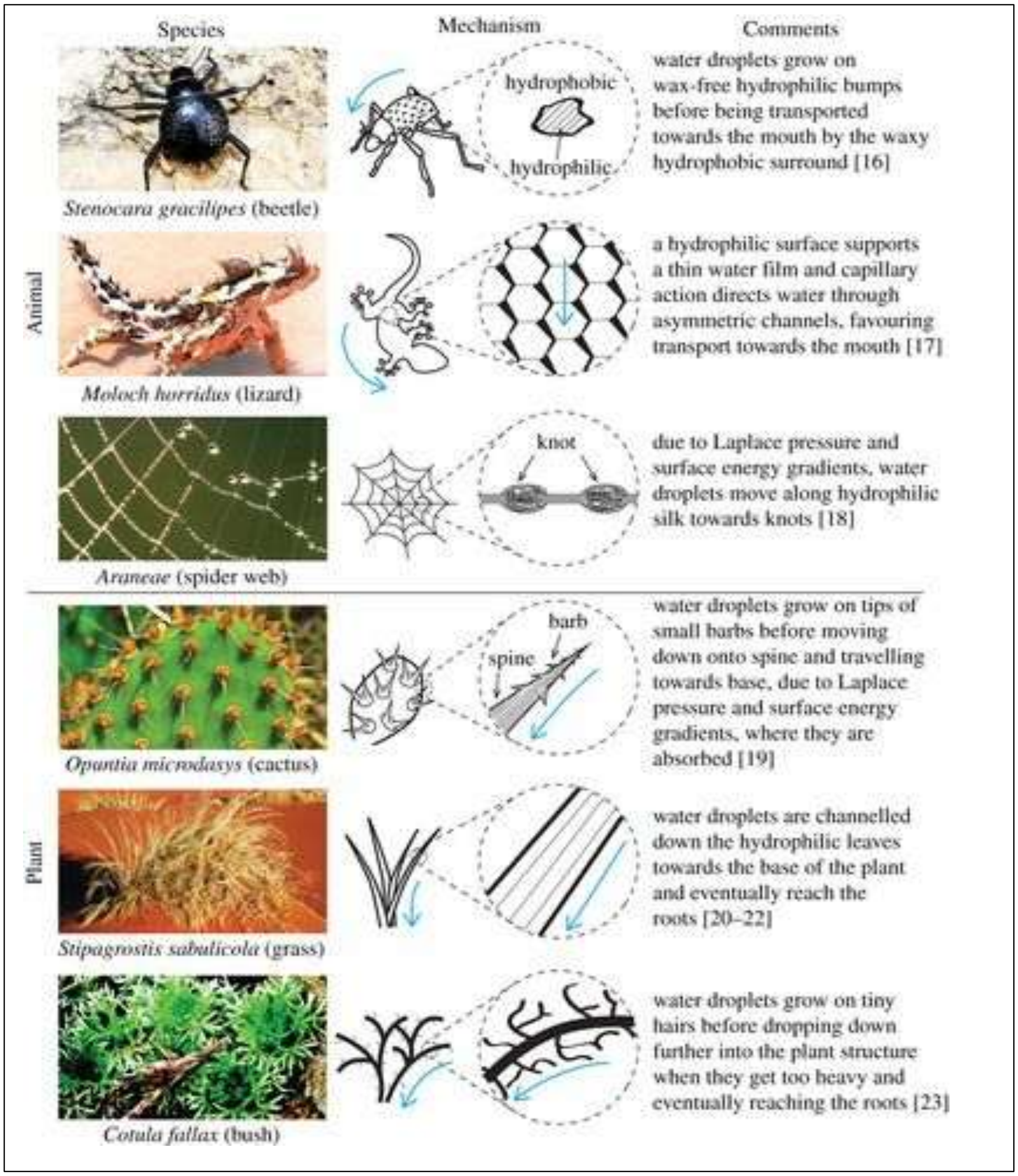

Figure 5. An overview of the plant and animal species that have drawn water from fog. Water is captured from fog and transported to the mouth, roots, or other locations for utilization through a combination of chemical and structural processes [96]

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