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7. Recent Update on Emerging Trends in Solar Technology for Water Purification: A Sustainable Water Management Approach

Shuvendu Shekhar Mohapatra

Crop Improvement Division,
ICAR-National Rice Research Institute,
Cuttack, Odisha.

Anuprita Ray

School of bioengineering and biosciences,
Lovely Professional University,
Phagwara, Punjab.

Abstract:

Sustainable water management is highly needed in the present scenario to meet the water requirement of growing population in the World. Solar energy has been a promising approach for water purification as an alternative to the existing traditional practice. Solar steam generation and steam re-condensation is one of the latest techniques to utilize the solar energy for water purification, desalination and distillation. The use of carbon nanotube – modified flexible wood membrane is found to be flexible, portable, recyclable, and efficient solar steam generation device for low-cost solar steam generation applications. A novel technology uses bi-layered structure of wood and Graphene oxide which is found to be very efficient in solar steam generation and desalination of sea water.

The Graphene oxide is layered on the micro porous wood which provides broad optical absorption and high photo thermal conversion culminating in increased temperature at the liquid surface. The wood - Graphene oxide combination showed a solar thermal efficiency of around 83 % under simulated solar excitation at a power density of 12kW/m2.

This structure is scalable and cost-effective for applications like large light absorption, photo thermal conversion, and heat localization. Nanophotonics-enabled solar membrane distillation (NESMD) has come out as a promising solution to make sea water suitable for human use. The NESMD technology uses highly localized photo thermal heating induced by solar illumination driving the distillation process. This technology can be scaled to larger systems with increased efficiency at higher ambient temperature which makes it useful for house hold and community – scale desalination. Solar energy can also be used to remove pharmaceuticals from water in a process called phenton – type method. In this process the nontoxic common reagents and solar energy is used to remove recalcitrant contaminants with reduced cost. This review focuses with the latest developments to use solar energy for sea water and waste water treatment and making the water suitable for human use.

Keywords:

Nanophotonics Enabled Solar Membrane Distillation (NESMD), Graphene oxide-assisted membranes, PVDF Membrane, Carbon Black.

7.1 Background:

Distillation is the most common one of many processes available for water purification, and sunlight is one of the most preferable non-conventional sources of heat energy that can be used to power that process. Sunlight has the prime advantage of zero fuel cost but it requires more area for set-up. To drive out a common belief, it is not needed to boil water to distill it. Basically, elevating its temperature, short of boiling point, will sufficiently increase the evaporation rate constantly. In reality, although dynamic boiling hastens the distillation process it also can force unwanted residue into the distillate unit, defeating the process of purification. Additionally, to boil water with sunlight requires more costly apparatus than is desired to distill it a little more slowly without any boiling [1].

A lot of levels of purification can be achieved with this process, depending upon the proposed application. For people worried about the quality of their municipally-supplied drinking water and unhappy with other methods of supplementary purification available to them, solar distillation of tap water or brackish groundwater can be an agreeable, energy/cost-efficient option. Solar distillation systems can be small or large as per desire.

They are designed either to serve the needs of a single family, producing from ½ to 3 gallons of drinking water a day on the average, or to produce much greater amounts for an entire neighborhood or community [2]. In some parts of the world the scarcity of fresh water is partially overcome by covering shallow salt water basins with glass in greenhouse-like structures. Solar distillation of potable water from saline (salty)/brackish water has been experienced for many years in tropical and sub-tropical regions where fresh water is fright.

Though, where fresh water is abundant and energy rates are reasonable, the mainly cost-effective method has been to pump and purify it [3]. Solar water purification includes mainly two aspects; first aspect is the sediment/residue removal using carbon filter then, pathogenic substance elimination in the various due to heat generated by natural convection mechanism due to parabolic trough. Preliminary filtration is conceded by a carbon filter. Carbons filtration is a process of filtering, which uses a bed of activated carbon to eliminate contaminants and impurities using chemical adsorption mechanism [4].

Here, we discussed the mechanism of Nano-photonics enabled solar membrane distillation (NESMD), where extremely restricted photo-thermal heating is induced by the solar illumination alone carried the distillation process, entirely eliminating the constraint of heating the input water. Unlike MD, NESMD can be scaled to larger units and shows amplified efficiencies with declined input flow velocities [5].

Along with its increased efficiency at a higher optimized temperature, these characteristics all point to NESMD as a promising explanation for household or community-scale desalination process.

7.2 Nanophotonics Enabled Solar Membrane Distillation (NESMD):

Current desalination techniques supply solutions to the increasing water demands of the planet but need substantial electric-thermal energy, limiting their sustainable use where conventional power infrastructure may be occupied. Here, we described a direct solar energy driven method for desalination that utilizes the Nano-particle-assisted solar evaporation in membrane distillation arrangement. This scalable process is capable of providing sufficient clean water for family use in a dense footprint, potentially for off-grid desalination at the remote locations [6]. The photo-thermal membrane central to NESMD is a bi-layered structure consisting of a relatively thin (25 µm), optically gripping, porous, hydrophilic [polyvinyl alcohol (PVA)] coating deposited onto a commercial scaled polyvinylidene fluoride (PVDF) membrane (0.2-µm nominal pore size) (Fig. 1 A). Carbon black (CB) with a broadband absorption over the entire solar spectrum was dispersed into the PVA solution medium [7]. The optical characteristics of the CB-laden bi-layer photo-thermal membrane were characterized to determine an optimal deliberation range of CB absorbers to provide as a heat source for NESMD set-up [8]. Since the CB-laden membrane is a medium that is both strongly-optically scattering and absorbing, hypothetical calculations using a Monte Carlo photon transport method were needed to precisely describe the membrane's utility as a photo-driven heat source [9]. The diffuse reflectance at 600 nm for membranes within a range of CB concentrations reflects a decreasing reflectance for rising CB concentrations [10]. Furthermore, comparisons of NESMD and MD reveal additional opposing trends between these two processes (figure1.A&B). An additional key parameter of purification set-up is feed velocity. For membrane distillation (MD), the feed inlet temperature was the same, and the inlet temperature was chosen to match the power input of NESMD. For membrane distillation (MD), where the feed is pre-heated before entry into the membrane module, higher feed velocities decrease heat loss for the feed flow along with the membrane [11]. In addition, significantly less energy would be required for salt water re-circulation, which can be a significant factor in the overall energy use of conventional MD process [12]. An additional important factor that influences NESMD performance is the ambient operating temperature. Here, the flux dependence on ambient temperature is determined for both a bench-scale (black, 8.1 × 3.48 cm) and pilot-scale set-up (red, 100 × 10 cm dimensional) device under unfocused conditions [13]. The temperature difference between the feed and the distillate without illumination is zero in all cases. In both cases, the performance significantly improves (more than two times) when the ambient temperature is increased from 10 to 40 °C. Higher ambient temperatures also favor the larger-dimensioned system. The cross-flow velocities in the feed and distillate channels were 0.54 cm/s (flow rate, 17 mL/min) and 4.34 cm/s (flow rate, 136 mL/min), respectively and these analytical data were collected from various experimental protocols. The feed stream (saline stream) on the top of the membrane was a 1% NaCl solutions stored in a 500-mL Erlenmeyer flask, and de-ionized water was used for the distillate stream at the bottom of the membrane module [14]. The chosen 1% salinity to mimic the average salinity of sea water, which is a main saline water supply used inland. To preserve stable temperatures on both sides of the membrane module, the feed and distillate were cooled by 15-m-long unnerving coils submerged in a shaded ice bath before entering the NESMD membrane module. The feed and distillate were incessantly circulated through the membrane module using peristaltic pump set-up in a countercurrent flow mode, where feed and distillate streams flow in an opposite direction. Unlike Membrane Distillation, NESMD payback from increases in scale-up and in moderate operating temperatures, and requires only modest flow requirements for most favorable distillate conversion. The working performance of NESMD system can be further increased by incorporating heat recovery by re-circulating feed outlet back to feed inlet [15]. This would increase the water flux rate and improve overall energy competence because the net energy consumption per unit volume of purified water produced will be abridged [16]. Heat recovery mechanisms proposed for MD systems to use distillate heat generated from condensation and conductive heat transfer mechanism through the membrane via heat exchange to preheat the inlet water should work equally well for NESMD system. It should also be probable to use vacuum MD or air-gap MD geometry to reduce heating on the distillate side. In terms of thermodynamic presentation limits, thermal processes such as NESMD operate further from the theoretical second law reversible limit than Reverse Osmosis systems [17]. Though, the capability of NESMD system to directly connect solar energy for desalination is positive compared with the need to produce high-grade electrical energy for RO systems, which is limited by low working efficiency photo-voltaic conversion when solar panels are used [18].

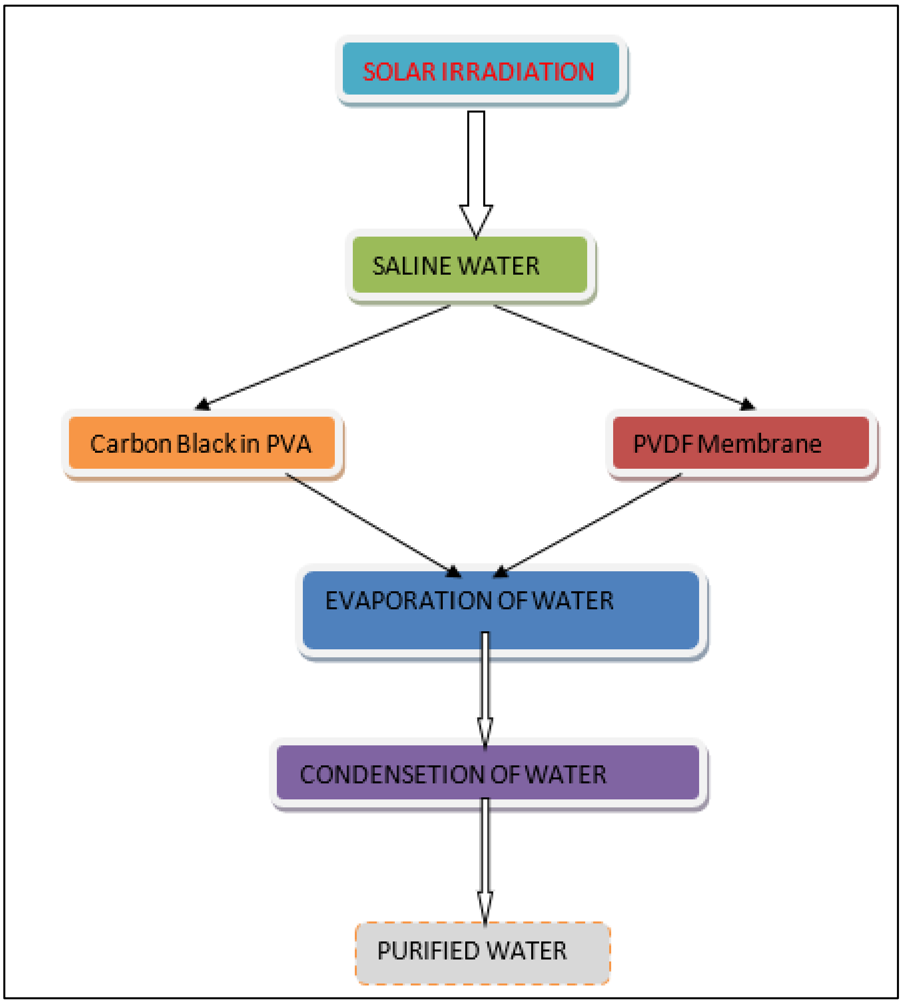

Figure 7.1.a: Graphical representation of the water purification technique through NESMD.

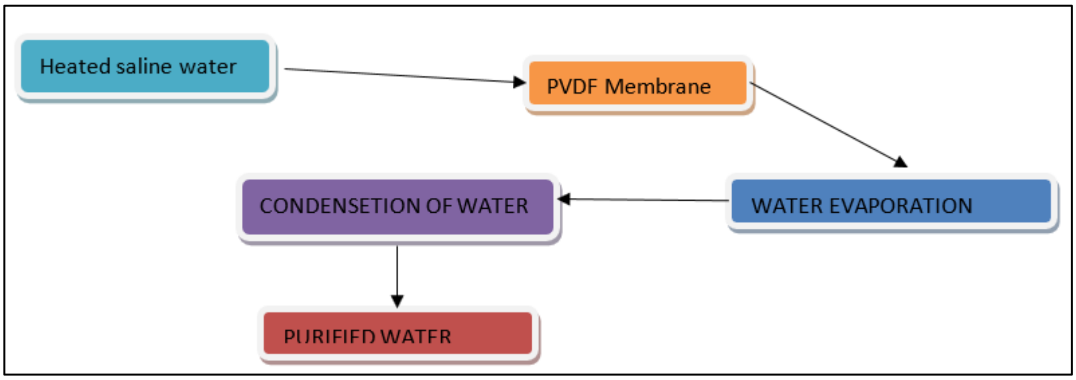

Figure 7.1.b: pathway for conventional water purification through membrane distillation

7.3 Graphene Oxide-Assisted Membranes: Potential Applications in Desalination and Water Purification

Worldwide, the problem of fresh water shortage has continued to go sky-high. One of the most influential techniques to fully safe and sound the availability of fresh water is desalination. Searching for more efficient and low-energy-consumption desalination protocol is the highest precedence on the research outline. Current progress has been achieved using grapheme- oxide (GO)-embedded membranes in desalination applications. GO's copious functional groups, including the epoxide, carboxyl and hydroxyl, endow with functional reactive sites and hydrophilic properties. Its self-supporting membrane, with a thickness of a small number of nanometers, has been functional recently in pressure driven membrane filtration process, which is a perfect candidate for the application of desalination membranes in the water purification protocols [19]. The multilayer GO laminates have an exceptional structural design and superior performance that enable the expansion of novel desalination membrane technology in water purification. With high-quality mechanical properties, they are effortlessly fabricated and have the ability to be industrially scaled up in the future generations. This review considers the different fabrication and amendment strategies for various pioneering GO-assisted desalination membranes, including self-supporting GO membranes, GO-surface-modified membranes and casted GO-incorporated membranes for desalination. Their desalination presentation and mechanism will be discussed, and their further opportunities and challenges will be decorated. Membrane fouling specific, high energy insist and trade-offs between salt rejection and water fluxes are remained as challenges of water desalination membranes in purification. In universal, the operating cost effectiveness of the RO process remains high because of the challenges of limited water permeability postulates, and high energy and chemicals consumption effect. Even though the required operational pressure in contemporary systems is close to the thermodynamics limits, additional reduction of the applied pressure will have no noticeable impact on performance level. Cohen-Tanugi et al. experiential that a tripling in permeability would be decreased the pressure by 44% and 63% for RO seawater and BW plants in that order; this is corresponding to a reduction of 15% and 46% in energy consumptions [20]. The drop in energy consumption would be important because of the high cost of the energy, which balance sheet for 50% of the total water desalination process cost. Membrane fouling is one of the most important concerns in desalination technology; the beginning of fouling gives rise to a decline in the RO membranes' performance which is actually adverse. Frequently, membrane fouling occurs via one of the two mechanisms: the first is the fouling layer in membrane pores of the system; the second is the membrane module surface fouling mechanism. Since Geim and Novoselov were awarded the Nobel Prize in Physics in the year of 2010, Graphene research has urbanized speedily in both rural and industrial applications. Graphene is an intended layer of strongly packed pure carbon atoms that are associated together in a hexagonal honey-comb shaped matrix design. More comprehensively, it is a carbon allotrope arranged in flat sp2- bonded atoms with a very minute molecule having the bond length of (0.142 nm) [21].

Graphite is a three-dimensional material produced by the arrangement of Graphene layers on top of each other carbon chains, with minute (0.335 nm) inter-planar gaps. This original material has progressed speedily towards scaling up production of 30-inch Graphene membranes comprising of multiple layers of Graphene sheet layers. The minute thickness of Graphene, i.e. one atomic layer has an exceptional tensile strength. Though this particular atomic layer is impermeable to all gases and liquids (Figure 7.2), many researchers are exploring the prospect of using this material to develop new membranes for desalination process and its applications. The presently available mass production of Graphene makes this development achievable. Furthermore, Nano-pores could be formed within the unsaturated carbon atoms, which subsist at the chemically constructed pore edge, in the configuration of Graphene. Newly, experimental trial for introducing nonpores into graphene has been widely explored and rapid developments achieved [22].

Original methods were based on electron beam bombardment; though, the more modern approaches such as helium ion beam drilling, di-block copolymer tinplating and chemical etching were performed to achieve higher pore density and more precise pore size circulation (Figure 7.2).

The most current studies have focused on using the prepared Nano-porous Graphene in gas partition and deoxyribonucleic acid (DNA) sequencing applications. Additionally, the competence of NaCl rejection by Graphene membrane was simulated using a molecular dynamics, simulation and modeling approaches. This bactericidal capability is durable over time, enabling a new kind of antimicrobial surface that is not decreasing or leaching. Liu et al. compared four derivatives of Graphene-linked materials Graphene oxide (GO), compact Graphene oxide (rGO), graphite (Gt) and graphite oxide (GtO) in terms of their anti-bacterial activity [23] against the bacterial spores of Escherichia coli.

Consequently, it was anticipated that pristine Graphene should be chemically customized in order to be practically utilized in several applications [24]. The three techniques comprise graphite oxidation to serious levels. Brodie and Staudenmaier oxidize the graphite using a combination of nitric acid (HNO_3) and potassium chlorate ($KClO_3$); in disparity, the Hummers method oxidizes the graphite using a mixture of potassium permanganate (KMnO4) and sulphuric acid (H_2SO_4).

The obtained graphite salts arranged via intercalating graphite with strong acids i.e., (H_2SO_4), HNO_3 or $HClO_4$ are produced prior to the oxidation of graphite [25] and, lastly, the exfoliation of GO in water, in order to obtain GO nanosheets as schematized in Figure 7.2.

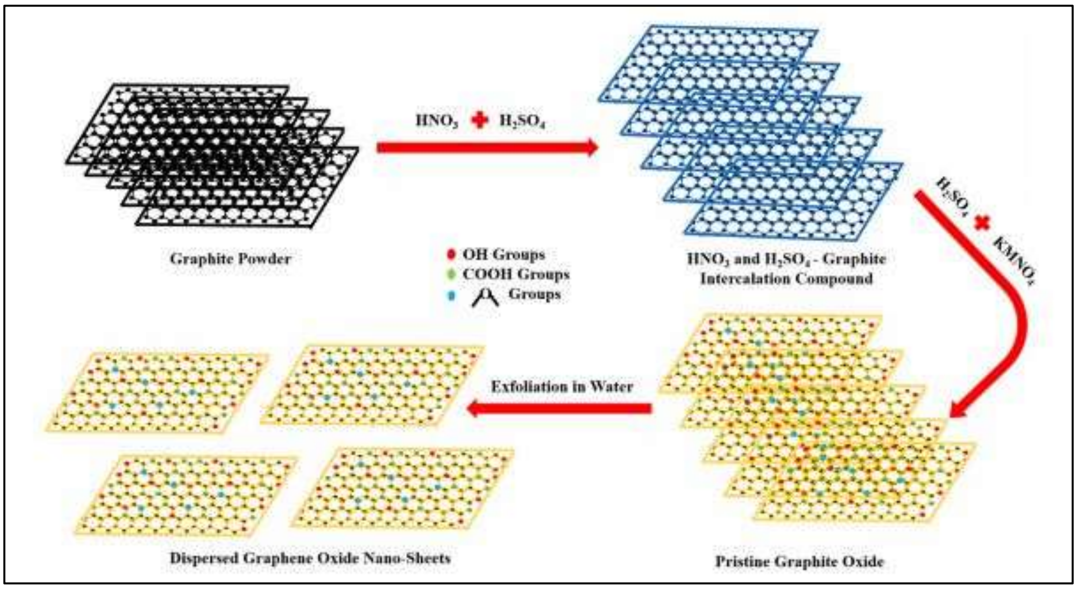

Figure 7.2: Graphene Oxide Nano sheet embedded model – snip taken from H.M. Hegab, L. Zou / Journal of Membrane Science 484 (2015) 95–106

7.4 Conclusion:

Current desalination technologies provide the solutions to the increasing water demands of the huge population but require substantial electric energy, restraining their sustainable use where conventional power infrastructure may be occupied. Here, we report the alternative comparison of direct solar method for desalination that utilizes nanoparticles-assisted solar vaporization in membrane distillation geometry. This scalable method is proficient of providing sufficient clean water for family use in a compact footprint, potentially for off-grid desalination at distant locations. Direct solar desalination, which produces desalinated water directly using solar energy with least carbon footprint, is considered a promising technology to address the global water scarcity.

Here, we report the effectiveness and advancement of the solar desalination device, with efficient two-dimensional water supply and suppressed thermal loss, which can enable an efficient (80% under one-sun illumination) and efficient (four orders salinity decrement) solar desalination. The energy transfer efficiency of this foldable Graphene oxide film-based device fabricated by a scalable process is independent of water quantity and can be achieved without optical or thermal supporting systems, consequently significantly improving the scalability and feasibility of this technology toward a complementary portable and personalized water solution.

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