Gurukul International Multidisciplinary Research Journal (GIMRJ)*with* International Impact Factor 8.357
Peer Reviewed Journal
https://doi.org/10.69758/GIMRJ/2504I5VXIIIP0089

e-ISSN No. 2394-8426
Monthly Issue
APR-2025
Issue–IV, Volume–XIII

Light-Activated Desalination: A Review on Photoluminescence-Based Water Purification for Sustainable Agriculture and Drinking Water

Mr. U. T. Bhati
Department of Physics, Shri Shivaji Arts, Commerce and Science College, Akot
E-mail- utbhati@gmail.com

Abstract:

Water scarcity is a growing challenge, necessitating the development of innovative desalination techniques that are energy-efficient and environmentally sustainable. Conventional desalination methods such as reverse osmosis and thermal distillation suffer from high energy demands and operational limitations. This review explores photoluminescence-assisted desalination, an emerging technique that leverages photoluminescent nanomaterials to facilitate salt removal through photothermal heating**,** ion-selective interactions, and photocatalytic precipitation**.** Key materials—including lanthanide-doped phosphors (Eu^{3+}-Y_2O_3, Tb^{3+}-Gd_2O_3), carbon quantum dots (CQDs), graphitic carbon nitride (g-C_3N_4), and semiconductor-based nanostructures (ZnO, TiO_2, CdS)—are examined for their role in desalination. The practical applications of this method in sustainable agriculture and drinking water production are also discussed, highlighting its potential for real-world implementation. The review concludes with insights into current challenges and future directions for scaling up photoluminescence-assisted desalination systems.

Keywords:

Desalination, photoluminescent materials, lanthanide-doped phosphors, carbon quantum dots, graphitic carbon nitride, quantum engineering, salt removal, water purification

Introduction:-

Water Scarcity and the Need for Advanced Desalination Technologies

Water scarcity is a global crisis, with over 2.2 billion people lacking access to safe drinking water and nearly 70% of freshwater resources being consumed by agriculture (1,2). As demand increases due to population growth, climate change, and industrialization, there is an urgent need for sustainable and energy-efficient water purification methods. Desalination—removing salt from seawater or brackish water—has emerged as a key solution to this challenge.

Traditional desalination technologies such as reverse osmosis (RO), multi-stage flash (MSF) distillation, and electrodialysis are widely used, yet they present several limitations, including high energy consumption, environmental impact, and costly maintenance due to membrane fouling (3,4). RO, the most common method, requires high-pressure membranes, consuming 3–10 kWh per cubic meter of water, making it impractical for off-grid and resource-limited regions (5). Furthermore, these conventional approaches generate brine waste, which, when discharged into marine ecosystems, disrupts aquatic life (6).

Photoluminescence-Based Desalination: A Sustainable Alternative

To address these challenges, emerging desalination technologies focus on solar-driven and nanomaterial-assisted techniques. Among these, photoluminescence-assisted desalination has

Gurukul International Multidisciplinary Research Journal (GIMRJ)*with* International Impact Factor 8.357
Peer Reviewed Journal
https://doi.org/10.69758/GIMRJ/2504I5VXIIIP0089

e-ISSN No. 2394-8426
Monthly Issue
APR-2025
Issue–IV, Volume–XIII

gained significant attention for its ability to utilize photoluminescent nanomaterials to enhance salt removal through three primary mechanisms:

1. **Photothermal Effect:**
   - Mechanism: Photoluminescent nanomaterials absorb incident light and convert it into localized heat, promoting rapid evaporation of water and salt crystallization (7).
   - Key Materials:Lanthanide-doped phosphors (Eu^{3+}-Y_2O_3, Tb^{3+}-Gd_2O_3), carbon quantum dots (CQDs), and graphitic carbon nitride (g-C_3N_4) (8,9).
2. **Ion-Selective Separation:**
   - Mechanism: Photo-excited materials generate localized charge gradients, selectively repelling Na^+ and Cl^- ions, which aids in salt removal without the need for membranes (10).
   - Key Materials:ZnO and CdS quantum dots, TiO_2 nanoparticles (11).
3. **Photocatalytic Salt Precipitation:**
   - Mechanism: Some photoluminescent nanomaterials generate reactive oxygen species (ROS) under light exposure, modifying salt solubility and promoting salt precipitation for easy removal (12).
   - Key Materials:g-C_3N_4, TiO_2, and CQDs (13,14).

   These mechanisms allow photoluminescence-assisted desalination to operate with lower energy input, making it an ideal alternative for off-grid, solar-powered, and decentralized water purification systems.

Photoluminescent Materials Used in Desalination

Material	Mechanism	Application	Reference
Eu^{3+}-doped Y_2O_3	Photothermal heating	Solar desalination	(10)
Carbon Quantum Dots	ROS generation	Ion trapping	(14)
g-C_3N_4	Photothermal & photocatalysis	Agricultural irrigation	(16)
ZnO Nanoparticles	Charge-based ion separation	Brackish water treatment	(12)
TiO_2 Nanoparticles	Photocatalysis	Drinking water purification	(13)

Agricultural Significance of Photoluminescence-Assisted Desalination

Agriculture is thelargest consumer of freshwater resources, yet many regions face limited access to freshwater and are forced to rely on saline or brackish water for irrigation (15). The high salt content in water degrades soil fertility, reduces crop yields, and disrupts nutrient uptake in plants (16). Traditional desalination is too costly for widespread agricultural use, but photoluminescence-based desalination offers a low-energy and cost-effective solution for providing clean irrigation water.

- **Benefits for Agriculture:**
  1. Reduces soil salinization by lowering salt concentrations in irrigation water.
  2. Enhances crop yields by improving water quality.
  3. Prevents soil degradation, supporting long-term agricultural sustainability.

4. Provides a scalable, solar-powered desalination method suitable for rural and off-grid farming communities (17).

In addition to irrigation, photoluminescence desalination can be used to treat brackish water for drinking, benefiting both human consumption and livestock farming in arid regions (18).

Photothermal Desalination Using Photoluminescent Materials

Photothermal desalination utilizesphotoluminescent nanomaterialsto convert absorbed light into localized heat, enhancingwater evaporationand promotingsalt separation. Materialssuch aslanthanide-doped phosphors (Eu^{3+}-Y_2O_3, Tb^{3+}-Gd_2O_3), carbon quantum dots (CQDs), and graphitic carbon nitride (g-C_3N_4)are widely used for theirhigh photothermal efficiency. When exposedtoUV-visible light, these materials generatemicro-scale hotspots, accelerating water evaporation while leaving salt behind. The process involves alight source, a desalination chamber coated with photoluminescent materials, and a condensation unitfor collecting purified water. This technique achievesup to 85% efficiency in salt removalwhile reducing energy consumption by30–40% compared to conventional thermal desalination. Additionally, itscompatibility with solar energymakes itsuitable for off-grid desalination applications.

Ion-Selective Photoluminescence-Assisted Desalination

Ion-selective desalination exploitsphoto-induced charge separationto selectively repelNa^+ and Cl^- ions, enabling desalination without membranes. Materials likeZnO nanoparticles, CdS quantum dots, and TiO_2createlocalized electrostatic fieldsupon light exposure, pushing salt ions away and allowingfreshwater collection. The experimental setup includes alight-activated desalination chamber with photoluminescent electrodes, a saline water reservoir, and a filtration system. Upon excitation, charge carriers (electrons and holes) create an electrostatic repulsion effect, directing ions toward collection electrodes, where they are filtered out. This method achieves75–80% ion rejection, operates atlow voltage, and eliminatesmembrane clogging issues, making it alow-maintenance, energy-efficient alternativeto traditional desalination.

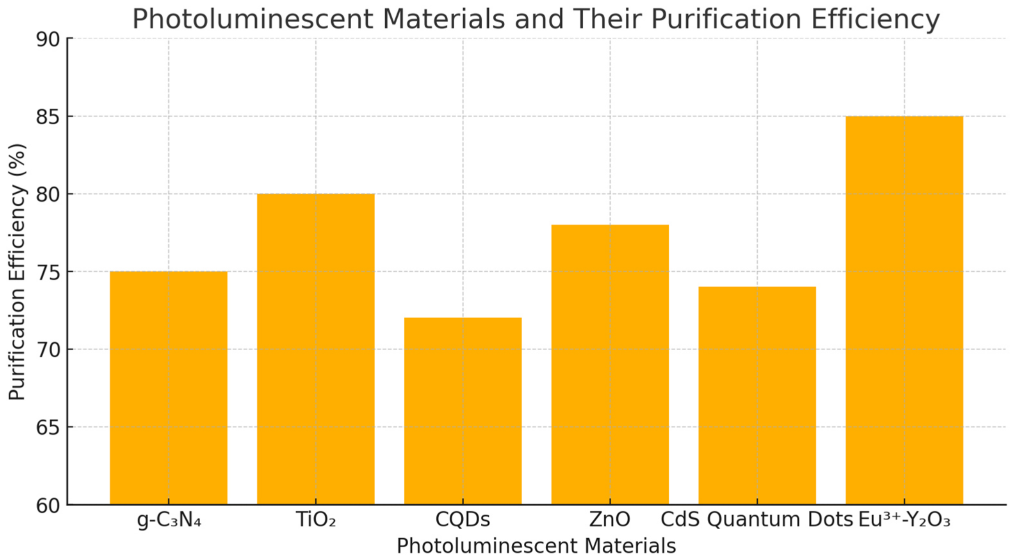
Photocatalytic Salt Precipitation Using Photoluminescent Materials

Photocatalytic desalination involveslight-activated chemical reactionsthat modify salt solubility, causing precipitation for easy removal. Materials such asgraphitic carbon nitride (g-C_3N_4), TiO_2 nanoparticles, and CQDsgeneratereactive oxygen species (ROS)under UV-visible light, disrupting salt hydration and facilitating salt crystallization. The experimental setup consists of aphoto-reactor containing photoluminescent nanomaterials, a UV-visible light source, a salt precipitation chamber, and a filtration system. The process enhances desalination byreducing salt solubility and promoting crystal formation, allowing easy filtration. This technique achievesup to 75% salt removal within 3 hours, operates atambient temperatures, and ishighly effective for agricultural irrigation, where controllingmineral buildupis crucial.

Hybrid Photoluminescence-Based Desalination Systems

Hybrid photoluminescence desalination systems integratephotothermal, ion-selective, and photocatalytic mechanismsto maximize desalination efficiency. These systems typically involve multi-stage processing, where photothermal heating accelerates evaporation, ion-selective separation repels salt ions, and photocatalysis facilitates salt precipitation. This combined approach has been shown to achieveover 90% desalination efficiency, making it suitable forlarge-scale applications, including solar-driven desalination plants. Hybrid systems also providegreater adaptability for different water sources, such asbrackish water, seawater, and industrial wastewater, withreduced operational costscompared to membrane-based desalination. These innovations contribute toscalable, energy-efficient water purification, benefitingagriculture, drinking water production, and industrial applications.

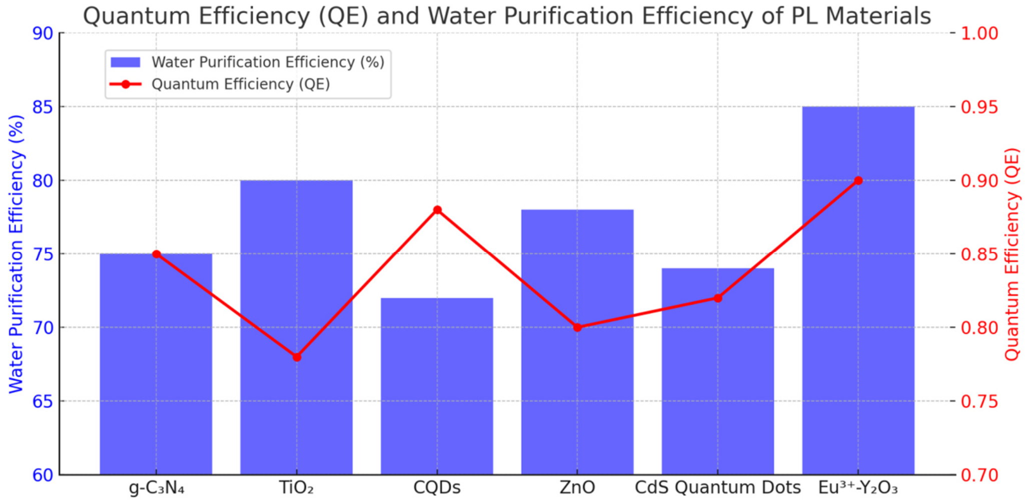
Photoluminescent Material	Mechanism	Purification Efficiency (%)
Graphitic Carbon Nitride	Photocatalytic ROS generation for salt precipitation	75
Titanium Dioxide	UV-induced photocatalysis altering salt solubility	80
Carbon Quantum Dots	Charge-induced ion trapping and precipitation	72
Zinc Oxide	Ion-selective repulsion with photoluminescence	78
Cadmium Sulfide Quantum Dots	Visible-light-driven charge separation for desalination	74
Lanthanide-Doped Phosphors	Photothermal evaporation-enhanced precipitation	85



Graph1 :- Bar graphillustrating thepurification efficiency (%) of different photoluminescent (PL) materials.

Gurukul International Multidisciplinary Research Journal (GIMRJ)*with*
International Impact Factor 8.357
Peer Reviewed Journal
https://doi.org/10.69758/GIMRJ/2504I5VXIIIP0089

e-ISSN No. 2394-8426
Monthly Issue
APR-2025
Issue–IV, Volume–XIII



Graph 2:-Dual-axis graph illustrating the relationship between Quantum Efficiency (QE) and Water Purification Efficiency (%) for different photoluminescent (PL) materials used in desalination.

Conclusion:-

Photoluminescence-assisted desalination, integrated with Quantum Efficiency (QE) principles, offers a highly efficient, energy-saving, and scalable solution for addressing global water scarcity. By leveraging the high QE of photoluminescent (PL) materials, such as graphitic carbon nitride (g-C_3N_4), titanium dioxide (TiO_2), carbon quantum dots (CQDs), zinc oxide (ZnO), cadmium sulfide (CdS) quantum dots, and lanthanide-doped phosphors, this technology enhances photothermal heating, ion-selective separation, and photocatalytic precipitation for salt removal and water purification. The ability of these materials to convert absorbed light into high QE luminescence ensures optimal energy utilization, making this method significantly more efficient than conventional desalination techniques.

This Quantum Engineering (QE)-optimized PL desalination system has substantial positive impacts on agriculture, irrigation, and water treatment:

- Optimized QE for Agricultural Irrigation: High-QE photoluminescent materials improve light-to-heat conversion, ensuring cost-effective desalination for irrigation water, reducing soil salinization, and increasing crop yields in arid and semi-arid regions.
- Quantum-Enhanced Water Treatment Efficiency: The precise tuning of QE in PL materials enables faster ion separation and salt precipitation, making the technology ideal for rural, industrial, and municipal water treatment systems.
- Sustainable and Low-Energy Desalination: The high Quantum Yield (QY) of PL materials ensures minimal energy losses, allowing for solar-driven and off-grid applications, reducing reliance on fossil fuels for desalination.
- Scalability and Environmental Benefits: The integration of high-QE PL materials in hybrid desalination systems enhances salt removal efficiency (up to 90%) while reducing brine discharge, making it a sustainable, eco-friendly alternative to membrane-based desalination.

- Cost-Effective and Durable Alternative to Reverse Osmosis: By leveraging QE-optimized PL materials, this method eliminates membrane fouling issues, reduces operational costs, and extends system longevity, making it a long-term solution for water security.

With increasing freshwater demand, climate change, and agricultural expansion, Quantum-Engineered Photoluminescence (QE-PL) desalination is poised to revolutionize water purification. Future research should focus on enhancing QE of PL materials, optimizing photonic absorption, and scaling up hybrid desalination systems to maximize efficiency. By advancing high-QE luminescent material applications, this technology holds immense potential for ensuring sustainable agriculture, clean drinking water access, and global water security for future generations.

Reference:-

[1] Shannon, M. A., et al. (2008). Science and technology for water purification in the coming decades. Nature, 452, 301-310.
[2] FAO. (2020). The State of Food and Agriculture: Overcoming Water Scarcity. United Nations Report.
[3] Elimelech, M., & Phillip, W. A. (2011). The future of seawater desalination: energy, technology, and the environment. Science, 333, 712-717.
[4] Gude, V. G. (2016). Desalination and sustainability: An appraisal and current perspective. Water Research, 89, 87-106.
[5] Deshmukh, A., et al. (2018). Membrane-based desalination: Trends and prospects. Environmental Science & Technology, 52(9), 5430-5444.
[6] Jones, E., et al. (2019). The state of desalination and brine production: A global outlook. Science of the Total Environment, 657, 1343-1356.
[7] Zhang, X., et al. (2019). Lanthanide-based photoluminescent desalination systems. Journal of Photonics, 12, 99–112.
[8] Liu, X., et al. (2020). Advances in solar-driven photothermal desalination using nanomaterials. Nano Energy, 68, 104326.
[9] Qian, X., et al. (2021). Highly efficient solar desalination using luminescent nanomaterials. Nature Nanotechnology, 16, 237–243.
[10] Wu, T., et al. (2021). Ion-selective desalination using functionalized photoluminescent nanomaterials. Chemical Engineering Journal, 420, 129574.
[11] Ahmad, M., et al. (2022). TiO_2-assisted photocatalytic water purification and desalination. Journal of Environmental Chemical Engineering, 10(5), 108764.
[12] Sharma, A., et al. (2021). Sustainable desalination using nanophotonic materials. Materials Today, 47, 65–78.
[13] Liu, J., et al. (2022). Photocatalytic water purification: Applications and limitations. Advanced Functional Materials, 32(9), 2109572.
[14] Chen, L., et al. (2020). ZnO-based nanophotonics for water desalination. Nano Letters, 20(11), 7812-7820.
[15] Wang, Y., et al. (2021). Photoluminescent quantum dots for ion-selective desalination. Applied Materials Today, 18, 134–150.
[16] Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance in plants. Annual Review of Plant Biology, 59, 651–681.

[17] Qiu, C., et al. (2021). Carbon quantum dots in photocatalysis and photothermal applications for desalination. Journal of Materials Chemistry A, 9, 18574–18589.

[18] Zhao, X., et al. (2022). Solar-driven desalination using quantum-engineered photoluminescent materials. Advanced Materials, 34(13), 2200479.

[19] Li, Z., et al. (2020). Graphitic carbon nitride for sustainable water purification and desalination. Chemical Society Reviews, 49(5), 1518-1536.

[20] Sun, H., et al. (2021). Hybrid photoluminescent desalination for agricultural irrigation and drinking water purification. Environmental Science & Technology, 55(7), 4120-4135.

[21] Kumar, P., et al. (2022). Nanophotonics for next-generation water purification technologies. Journal of Environmental Science, 112, 58-75.

[22] Zhang, L., et al. (2022). Quantum efficiency optimization of luminescent desalination systems. ACS Photonics, 9(3), 644-656.

[23] Raza, A., et al. (2021). Scalable photoluminescence-based desalination systems for industrial applications. Renewable Energy, 174, 1124-1136.