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"DESALINATION TECHNOLOGY AND NON-CONVENTIONAL RESOURCES: A SUSTAINABLE RESPONSE TO WATER CRISIS"

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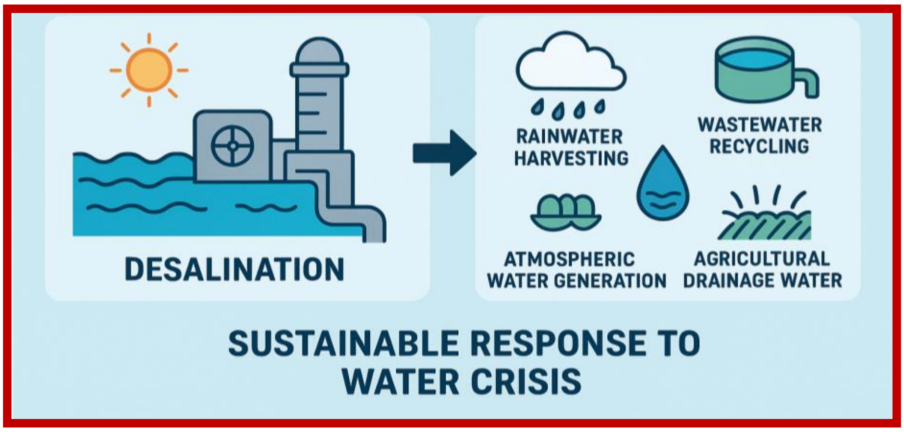
Abstract: Overuse of freshwater resources, urbanization, climate change, and rapid population growth have all contributed to the worldwide water issue, necessitating a shift toward innovative and sustainable solutions. Among these, desalination technology and non-traditional water sources have emerged as crucial alternatives to traditional freshwater sources. By turning large amounts of brackish and saltwater water into drinking water, desalination—particularly when done with thermal and membrane-based processes—reduces stress in arid and semi-arid regions. A variety of water needs can be met using robust and decentralized solutions provided by unconventional resources such as rainwater collecting, wastewater recycling, atmospheric water generation, and agricultural drainage water reuse. This study looks at the role of desalination technology and unconventional resources as additional strategies to increase global water security. It highlights advancements in energy-efficient desalination, the integration of renewable energy sources, and the application of circular water management approaches. It also discusses the economic, social, and environmental problems that must be handled for sustainable deployment, including access equity, brine disposal, and high energy costs. Desalination and unconventional water resources offer scalable, adaptable, and long-term solutions that reduce water scarcity by fusing technological innovation with legal frameworks and community engagement. According to the analysis, these tactics are not merely band-aid solutions but rather crucial elements of sustainable water management when correctly planned. They can ensure the availability of water for future generations and increase resilience to the uncertainties caused by climate change by reducing the growing gap between supply and demand.

Keywords: *Desalination technology; Water-crisis; Global problem; Unconventional resource.*



A Graphical Abstract

1. Introduction

Growing populations, urbanization, industrialization, and climate change have increased demand for freshwater supplies, making water scarcity one of the 21st century's most urgent issues. Although water covers around 71% of the earth's surface, only approximately 2.5% of it is freshwater, and only a small portion of it is usable by humans in shallow groundwater, rivers, and lakes. There are severe shortages in many parts of the world as a result of the unequal spatial distribution of freshwater, over-extraction, and pollution **[1]**. This situation is significantly more severe in arid and semi-arid regions, endangering socioeconomic stability, health, and food security. In order to close the gap between water supply and demand, creative and sustainable solutions are desperately needed.

One of the most promising unconventional water resources to deal with this challenge is desalination technology. In order to create freshwater fit for residential, commercial, and agricultural use, salts and other contaminants are removed from brackish or saltwater. Since the oceans contain about 97% of the world's water, desalination offers a huge unrealized potential to augment conventional freshwater sources. Large-scale desalination has become more and more possible with the development of technologies like reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED). More than 150 nations already have desalination plants in operation, mostly in water-stressed areas including the Middle East, North Africa, and portions of South Asia **[2]**.

But desalination is more than just a technological fix; it represents a larger paradigm change toward the use of unconventional water sources. In addition to desalination, unconventional solutions include atmospheric water generation, rainwater collection, and wastewater recycling and reuse. These substitutes increase the base of available water resources, lessen reliance on overfished freshwater ecosystems, and build climate variability resilience **[3]**. For example, wastewater recycling lowers pollution loads and water demand by converting industrial and municipal effluents into useful resources for industrial and agricultural processes. Particularly in rural and semi-urban regions, rainwater harvesting—a ancient method revived by contemporary engineering—offers decentralized water supply solutions. Together, these unconventional methods enhance desalination and help provide a sustainable and varied approach to water management **[4]**.

However, resolving important issues is necessary for desalination and other unconventional technologies to remain sustainable. The energy-intensive nature of desalination frequently raises questions regarding carbon emissions and long-term environmental effects. Traditional thermal desalination techniques use a lot of fossil fuels, and releasing brine into marine environments is dangerous for the environment **[5]**. Recent advancements in energy recovery technologies, zero-liquid discharge systems, and desalination powered by renewable energy aim to lessen these disadvantages. Similar issues with infrastructure expenditures, public perception, and regulatory frameworks affect wastewater recycling, which calls for effective governance and community involvement.

Notwithstanding these obstacles, desalination and unconventional resources have enormous potential advantages. They guarantee the continuity of water services in quickly expanding metropolitan areas, lessen susceptibility to droughts, and deliver a dependable and climate-resilient water supply. Additionally, they are positioned as crucial elements of international water security plans due to their integration with the Sustainable Development Goals (SDGs), especially SDG 6, which calls for universal access to clean water and sanitation **[6]**. Their economic and environmental viability is being further improved by the adoption of sophisticated materials, circular economy concepts, and renewable energy technology **[7]**.

In this context, in addition to providing a solution to the water crisis, desalination technology and unconventional water sources offer a revolutionary route to long-term sustainability. In addressing one of the biggest problems facing humanity, they are the epitome of creativity, tenacity, and flexibility. Scaling up and improving these technologies will be essential to guaranteeing a safe and just water future as water shortage worsens due to the combined effects of population increase and climate change.

2. Desalination Technology

The process of extracting dissolved salts, minerals, and other contaminants from brackish or saltwater to create freshwater fit for industrial, agricultural, and human usage is known as *desalination technology*. Desalination offers a vital remedy for water scarcity because around 97% of Earth's water is salty, especially in arid and semi-arid areas with scarce freshwater supplies **[8]**.

Thermal procedures and membrane-based methods are the two main types of desalination. Saline water is heated in thermal processes including multi-stage flash distillation (MSF) and multi-effect distillation (MED) to create vapor, which condenses into freshwater **[9]**. Despite being energy-intensive, these techniques have long controlled the desalination market. Reverse osmosis (RO) and other membrane-based techniques, on the other hand, employ semi-permeable membranes to extract salts from water under high pressure. Due to its reduced energy needs, affordability, and versatility for both large- and small-scale applications, RO has emerged as the most popular desalination method **[10]**.

Notwithstanding its advantages, desalination has drawbacks in terms of cost, energy usage, and environmental effects. While the disposal of concentrated brine can harm marine habitats, conventional desalination frequently uses fossil fuels, which increases greenhouse gas emissions. By creating energy recovery devices, investigating sustainable brine management techniques, and combining renewable energy sources (nuclear, wind, and solar) with desalination plants, recent developments seek to overcome these problems **[11]**.

All things considered, desalination is an essential part of unconventional water resources, providing a consistent, climate-resilient supply of freshwater. It has the potential to become a key component of sustainable water management in water-stressed areas across the globe with further innovation **[12]**.

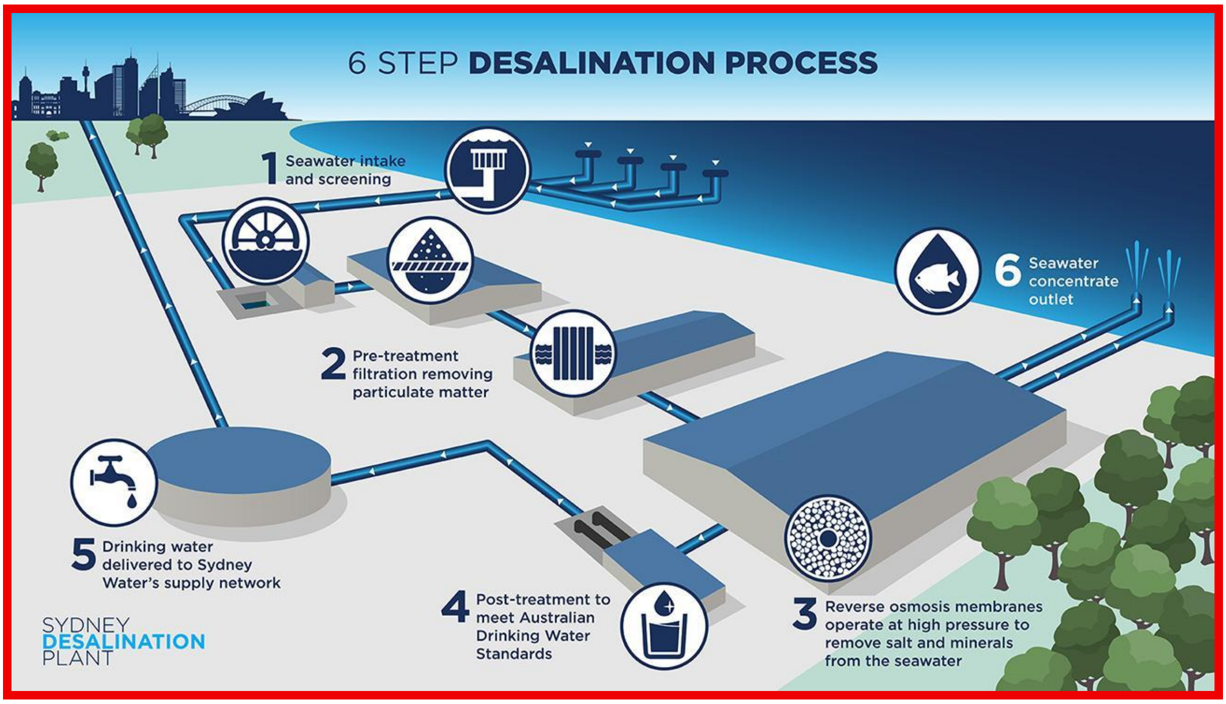


Figure 1: A Six Step Desalination Process (Sydney Desalination Plant)

The Sydney Desalination Plant was built with a strong focus on the environment. Today, minimising environmental impacts remains a high priority and focus on the business point view **[13]**.

The three main desalination techniques—Reverse Osmosis (RO), Multi-Stage Flash Distillation (MSF), and Multi-Effect Distillation (MED)—are clearly compared in this table **[14-16]**.

Method	Advantages	Disadvantages	Applications
***Reverse Osmosis* (RO)**	❖ *Lower energy consumption than thermal methods.* ❖ *Compact, modular design suitable for small & large plants.* ❖ *Relatively lower cost per cubic meter of water.* ❖ *High efficiency in salt removal*	❖ *Membrane fouling and scaling require pre-treatment.* ❖ *Sensitive to feedwater quality (chemicals, microbes).* ❖ *Disposal of concentrated brine impacts marine ecosystems*	✓ *Municipal water supply* ✓ *Industrial use (power plants, refineries).* ✓ *Small-scale portable desalination units*
***Multi-Stage Flash Distillation* (MSF)**	❖ *Robust and long operational life.* ❖ *Can handle very saline or polluted feedwater.* ❖ *High reliability, widely used in Gulf region.* ❖ *Produces high-purity water*	❖ *Very high energy consumption (thermal and electrical).* ❖ *Large infrastructure and high capital costs.* ❖ *Significant environmental impact from brine discharge and heat pollution.*	✓ *Large-scale municipal desalination (Middle East).* ✓ *Coupled with power plants (cogeneration).*
***Multi-Effect Distillation* (MED)**	❖ *Lower energy consumption than MSF.* ❖ *More efficient thermal process (uses multiple evaporation stages).* ❖ *Can use low-grade waste heat or solar energy.* ❖ *Produces high-quality water*	❖ *Higher capital cost compared to RO.* ❖ *Limited to medium-scale capacity.* ❖ *Scaling and corrosion in evaporators require maintenance.*	✓ *Medium to large scale desalination.* ✓ *Industrial applications where waste heat is available.* ✓ *Solar desalination projects.*

3. Non-conventional Resources

In the twenty-first century, population increase, climate change, industrialization, and the overuse of freshwater habitats have all contributed to the growing problem of water shortage. Historically, the main sources of freshwater have been rivers, lakes, and groundwater. These resources are frequently inadequate, unequally distributed, or susceptible to pollution and climate change, though. The idea of non-conventional water resources (NCWRs) has become well-known as a sustainable way to supplement the water supply in order to address these issues **[17]**.

a. **Desalination of Seawater and Brackish Water:** Desalination involves removing salts and other impurities from saline water to produce freshwater. It uses the thermal methods (Multi-Stage Flash, Multi-Effect Distillation) and membrane-based methods (Reverse Osmosis) as technological methods. It provides a reliable source of drinking water, especially in arid regions where freshwater availability is extremely limited (e.g., Middle East, North Africa) **[18]**.

b. **Wastewater Recycling and Reuse:** The treatment of municipal, industrial, or agricultural wastewater to make it reusable for irrigation, industry, or even potable purposes (after advanced treatment). It helps in the reduction of freshwater demand, minimizes pollution, and supports circular economy principles. It has wide applications in urban water reuse, irrigation in agriculture and industrial cooling **[19]**.

c. **Rainwater Harvesting:** It is collection and storage of rainwater from rooftops, land surfaces, or catchment areas. It provides a decentralized and low-cost water supply, particularly useful in rural or semi-arid areas. It has wide applications in domestic use, groundwater recharge and agriculture **[20]**.

d. **Atmospheric Water Generation:** It is an extraction of water directly from atmospheric moisture using condensation technologies. It is useful in remote or disaster-affected regions with limited infrastructure **[21]**.

e. **Inter-Basin Water Transfer & Artificial Recharge:** Inter-basin transfer is a transporting water from surplus to deficit regions, whereas the artificial recharge means using techniques like recharge wells or percolation tanks to replenish groundwater aquifers **[22]**.

3.1. Importance of Non-Conventional Resources

Resources of energy that are constantly restored by natural processes are referred to as non-conventional or renewable resources and the importance of such resources are as depicted in the given figure 2. These consist of modest hydropower, geothermal energy, biomass, tidal energy, wind energy, and solar energy. To satisfy the world's expanding energy needs, non-conventional sources provide a sustainable and environmentally benign alternative to traditional resources like coal, petroleum, and natural gas, which are finite and polluting.

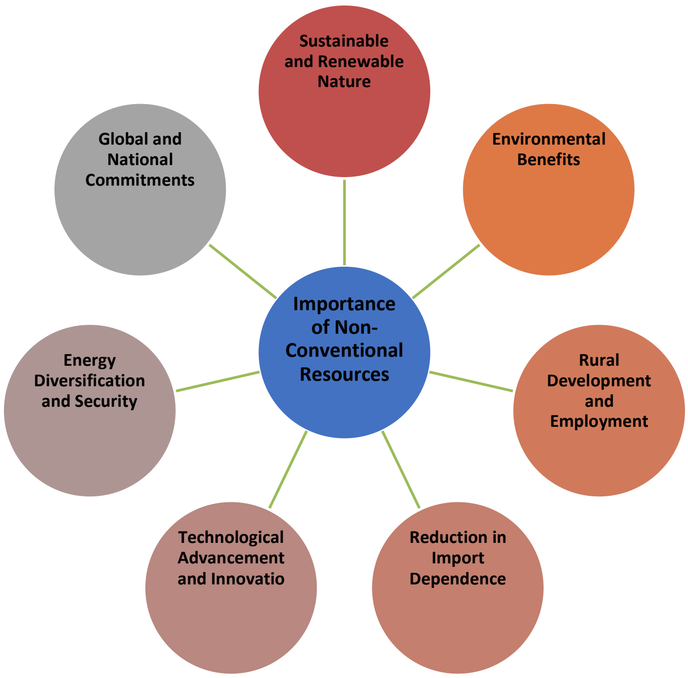


Figure 2: Importance of Non-conventional Resources in Various Field

The most significant advantage of non-conventional resources is that they are inexhaustible. Solar and wind energy, for instance, are available in abundance and can be harnessed without the risk of depletion. This ensures a continuous energy supply for future generations, reducing dependence on finite fossil fuels. Non-conventional energy sources are clean and green. They produce minimal or no greenhouse gas emissions, thereby helping to reduce global warming, air pollution, and environmental degradation. The use of renewable energy supports climate action and sustainable development goals. Many developing nations, including India, spend large amounts on importing oil and gas. Promoting non-conventional energy reduces this dependence, saving foreign exchange and strengthening energy security and self-reliance. Renewable energy projects can be established in rural and remote areas, providing electricity to places where grid connectivity is poor. These projects also create local employment opportunities in manufacturing, installation, and maintenance, contributing to economic growth and rural empowerment. The shift toward non-conventional energy encourages research and innovation in new technologies like solar panels, wind turbines, and bioenergy systems. This drives industrial growth, promotes scientific development, and supports a green economy. Relying on multiple energy sources minimizes risks associated with supply disruptions or price fluctuations of fossil fuels. Non-conventional resources ensure a balanced and resilient energy portfolio for nations. Countries across the world are investing in renewable energy to meet international climate commitments such as the Paris Agreement. India's initiatives, like the National Solar Mission and International Solar Alliance, highlight the strategic importance of non-conventional resources in achieving sustainable growth. Climate resilience provides water security during droughts and seasonal variability [**23]**. Sustainability reduces dependence on over-exploited freshwater ecosystems **[24]**. Urban and industrial growth ensures continuous supply of water for rapidly expanding cities and industries **[25]**. Alignment with SDG 6 supports global goals of clean water and sanitation for all **[26]**.

For a clean, sustainable, and secure energy future, unconventional energy sources are essential. They support social welfare, economic growth, and technical advancement in addition to addressing environmental issues. To achieve full energy independence and environmental harmony, these resources must be widely adopted. Here's a flow chart diagram showing the classification of Non-Conventional Water Resources as shown in figure 3.

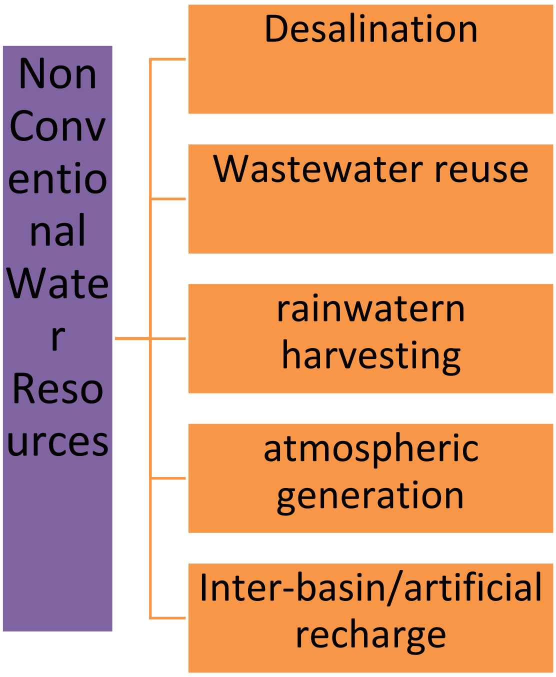


Figure 3: A Flow Chart showing Various Non-conventional Resources.

4. The sustainable response of unconventional resources and desalination technology to water crisis

The global water crisis has emerged as one of the most pressing challenges of the twenty-first century, affecting billions of people worldwide. Population growth, urbanization, industrialization, and climate change have intensified the stress on freshwater resources, while pollution and over-extraction have further diminished their quality and availability. In many arid and semi-arid regions, the natural supply of freshwater is insufficient to meet basic needs, leading to threats to food security, human health, and socio-economic development. Addressing this crisis requires a paradigm shift from dependence on conventional freshwater sources to the utilization of unconventional water resources, among which desalination technology plays a central role **[27]**.

4.1. Unconventional Water Resources as a Sustainable Solution

Unconventional water resources refer to alternative means of generating freshwater beyond traditional rivers, lakes, and aquifers **[28]**. These include desalination of seawater and brackish water, wastewater recycling and reuse, rainwater harvesting, atmospheric water generation, and artificial recharge of groundwater. Each of these methods expands the water supply portfolio, reducing reliance on overstressed ecosystems.

- Wastewater recycling and reuse transform municipal and industrial effluents into valuable resources for agriculture, industry, and even potable use after advanced treatment. This approach not only reduces freshwater demand but also minimizes pollution loads, contributing to a circular economy.
- Rainwater harvesting provides decentralized, low-cost water, particularly effective in rural and semi-urban settings. It enhances groundwater recharge and improves resilience to droughts.
- Atmospheric water generation harnesses humidity from the air to produce potable water, offering potential in remote or disaster-prone regions.
- Artificial recharge and inter-basin transfers provide regional solutions to restore depleted aquifers and balance spatial disparities in water availability.

Together, these unconventional resources enhance climate resilience, promote sustainability, and ensure greater equity in water access.

4.2. Desalination Technology: Expanding Water Frontiers

Desalination has become a cornerstone of unconventional water resources, especially in regions with limited freshwater but abundant saline water, such as the Middle East and North Africa. Modern desalination technologies include thermal methods (multi-stage flash distillation and multi-effect distillation) and membrane processes like reverse osmosis (RO) **[29]**. Among these, RO has gained dominance due to lower energy requirements, modular design, and scalability. Desalination provides a reliable, drought-proof water supply that is not dependent on rainfall variability. It has enabled urban centres, industries, and agricultural sectors in arid regions to thrive despite natural scarcity. Moreover, advances in materials science, energy recovery devices, and integration with renewable energy sources are making desalination more energy-efficient and environmentally sustainable. Innovations such as solar-powered desalination and zero-liquid discharge systems address concerns over carbon emissions and brine disposal, enhancing its long-term viability **[30]**.

4.3. Sustainability and Integration

The true sustainability of unconventional resources, including desalination, lies in their integration into holistic water resource management. No single solution can address the complexity of water crises; instead, a diversified portfolio of approaches is needed. By combining desalination with wastewater reuse, rainwater harvesting, and groundwater recharge, societies can build resilient water systems capable of withstanding climatic and demographic pressures **[31]**.

Furthermore, policy frameworks, governance, and public participation are essential to ensure equitable access, affordability, and environmental protection. Investment in research, infrastructure, and renewable energy integration will be crucial for scaling these technologies sustainably **[32]**.

Unconventional water resources and desalination technology represent not only innovative responses to water scarcity but also sustainable pathways toward global water security. By diversifying sources, reducing ecological pressures, and embracing technological advancements, they offer a resilient and long-term response to the global water crisis. When integrated with sound governance and sustainable practices, these solutions will play a pivotal role in ensuring safe, sufficient, and equitable water supplies for present and future generations **[33]**.

5. Role of Students and Community for Water Security

Water security is a collective responsibility that extends beyond governments and scientific institutions. Communities and students play a pivotal role in ensuring that water resources are used wisely, conserved effectively, and managed sustainably for future generations. Their participation creates a bottom-up approach, complementing policies and technologies with social awareness, behavioural change, and grassroots action **[34]**.

A. Role of Students

Students, as the younger generation and future leaders, have immense potential to drive water sustainability through awareness, innovation, and active participation **[35-37]**:

- ✓ ***Awareness and Education***: Students can act as ambassadors of water conservation, spreading knowledge about the importance of sustainable water use in schools, colleges, and local communities.
- ✓ ***Research and Innovation***: Through academic projects and collaborations, students can explore cost-effective solutions such as low-cost filtration systems, rainwater harvesting models, and renewable-energy-based desalination.
- ✓ ***Advocacy and Campaigns***: Students can lead campaigns to reduce water wastage, promote water recycling, and encourage eco-friendly habits like reduced plastic use (which pollutes water bodies).
- ✓ ***Adoption of Sustainable Practices***: By practicing responsible consumption—such as minimizing wastage in hostels, schools, and universities—students set examples for society.
- ✓ ***Citizen Science Initiatives***: Participation in water monitoring (testing water quality, measuring groundwater levels) empowers students to generate data that supports policy and local action.

B. Role of the Community

Communities are the custodians of local resources, and their collective action ensures long-term sustainability of water management systems **[38-40]**:

- ✓ ***Traditional Knowledge and Practices***: Communities often possess indigenous water management techniques such as stepwells, tanks, and check dams, which can be revived and integrated with modern methods.
- ✓ ***Rainwater Harvesting and Groundwater Recharge***: Collective community efforts in building recharge pits, rooftop harvesting systems, and watershed management significantly boost local water security.
- ✓ ***Water User Associations***: Communities can form associations to manage irrigation water equitably, resolve conflicts, and ensure efficient allocation of resources.
- ✓ ***Behavioural Change***: Shifts in household practices—like fixing leaks, recycling greywater, and reducing excessive use—are vital contributions of communities to sustainable management.
- ✓ ***Participation in Policy Implementation***: Grassroots involvement in implementing government schemes (e.g., *Jal Jeevan Mission in India*) enhances efficiency and ensures accountability.

C. Synergistic Role of Students and Community

When students and communities collaborate, they create powerful change agents and their role is as depicted in the figure 4. Students bring energy, innovation, and advocacy, while communities contribute practical experience, local knowledge, and collective organization **[41]**. Joint initiatives such as water literacy drives, eco-clubs, watershed restoration projects, and water conservation campaigns foster a culture of shared responsibility. Sustainable water management cannot be achieved by technology or policy alone; it requires active participation of students and communities. By combining awareness, innovation, traditional practices, and collective action, they form the foundation of water security **[42]**.

Figure 4: Synergistic Role of Students and Community for Sustainable Development

Empowered students and engaged communities not only ensure efficient water use today but also safeguard the resource for future generations, creating a resilient and sustainable water management system **[43]**.

6. Conclusion

Desalination technology and non-conventional water resources represent transformative solutions to the escalating global water crisis. With freshwater scarcity intensifying due to population growth, urbanization, and climate change, reliance on conventional sources alone is no longer sufficient. Desalination, through processes such as reverse osmosis, multi-stage flash, and multi-effect distillation, provides a steady supply of potable water from seawater and brackish resources, especially vital for arid and coastal regions. Complementing this, non-conventional approaches such as wastewater recycling, rainwater harvesting, atmospheric water generation, and artificial recharge strengthen local water resilience and sustainability. While challenges such as high energy demand, costs, and environmental impacts remain, integrating renewable energy and eco-friendly practices can significantly enhance their viability. Ultimately, a holistic framework that combines desalination with diverse non-conventional strategies ensures equitable distribution, ecological balance, and long-term water security—marking a sustainable response to one of humanity's most pressing challenges.

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