CHAPTER 1

INTRODUCTION

1.1 Water Scarcity

Water is not only a necessity for life but is also indispensable for carrying out social and economic activities in a country (Distefano and Kelly, 2017). Freshwater resources are experiencing shrinkage in availability and quality deterioration due to unprecedented growth in population, industrialization, and continuously changing weather conditions (Bixio et al., 2006). Due to the over-exploitation of available water and degradation in quality due to human activities, the world has entered a state of severe water crisis (Hertel and Liu, 2019). The 21st century is facing the problem of water scarcity, that is referred to as the scenario when the demand of water is higher than its availability (Pearce, 2018). The non-uniform spatial distribution of available freshwater resources is the primary reason behind water scarcity problems prevailing in various parts of the world (Damania, 2020). Water scarcity has been regarded as a global risk with potentially devastating impacts (Global risks report, 2019). As per the Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India (MoWRRDGR) (2020), water-stressed conditions exist when the annual per capita availability of water is less than 1700 cubic meter while water-scarce conditions will exist when the annual per capital water availability is less than 1000 cubic meter. India is predicted to get most severely impacted by water scarcity owing to its high urban population (He et al., 2021). To tackle this imbalance between water demand and its safe availability, wastewater reclamation is being seen as a potential source of water, which if treated, can boost water availability as well as prevent environmental degradation (van Zyl and Jooste, 2022). Treated wastewater is being considered as a reliable and economical solution to the problem of water scarcity (Goyal and Kumar, 2020).

1.2 Wastewater Reclamation

United Nations Global Water Report (UNGWR) remarked that the problem of water pollution and scarcity can be dealt with by reutilizing wastewater, which is still an "untapped" source (UNGWR, 2017). When treated wastewater is reutilized after treatment, it is referred to as wastewater reclamation (Asano, 1998). However, proper planning and implementation are needed for integrating such a system into the normal human-water cycle as any mismanagement can lead to huge costs or affect human health. Few countries have already moved forward in the direction of sustainable wastewater management. Reuse of wastewater for general utility purposes was first seen at Grand Canyon Village, Arizona, US, since 1925, where they utilized an Activated Sludge Process (ASP) based treatment plant for obtaining reclaimed water (Garthe and Gilbert, 1968), and now the country has progressed to safely use reclaimed water for managed aquifer recharge (Bernat, 2021). Direct potable reuse of treated wastewater is emphasized in the US, along with re-utilization in various other reuse purposes such as irrigation and other agricultural uses, laundry washing, industrial cooling, toilet flushing, fish propagation, etc. (Schmidt et al., 1975; Fito and Van Hulle, 2021). US Environmental Protection Agency (USEPA) published a quality criteria guideline defining the quality required, treatment technologies required, and sampling and monitoring guidelines (USEPA, 2012). Israel, being a water-stressed country, allows the non-potable reuse of reclaimed water after treatment through coastal aquifer recharge (Guttman et al., 2020). Wastewater reuse has been prevalent in Japan since 1968. It is a leader in the field of reclaimed water and several emerging technologies are still being developed for safe reclaimed water production. They have the dual-reticulation system as a part of their integrated wastewater and water supply network (Asano et al., 1996; Takeuchi and Tanaka, 2020). In Europe, quality standards for reclaimed water suitable for re-utilization in irrigation have already been published, especially in Mediterranean countries like Spain, Greece, and Italy (Roccaro and Verlicchi, 2018). In California and Florida, quality requirements of reclaimed water for various purposes like irrigation were defined way back in the 1970s, and integration of reclaimed water reuse in the social system is in a moderately developed state (Coe and Laverty, 1972; Florida, 1995; Capodaglio, 2021). In China, wastewater reclamation is based on strict compliance to the desired quality, water metering, and reuse can be seen in various non-potable reuses such as toilet flushing, recreation, laundry washing, vehicle washing, etc. (Chen et al., 2017). Similarly, successful efforts in wastewater reclamation for potable and non-potable purposes can be seen in Singapore (Ghernaout, 2019), Namibia (Haarhoff and Van der Merwe, 1996), etc. By observing the trend of water demand and the definition of relevant quality criteria, raw wastewater can be treated to produce a secondary water source (Reyes, 2022).

In the past two decades, the importance of wastewater treatment has become more apparent due to the prevalence of epidemics, like the ongoing COVID-19 infection which has affected millions of lives worldwide (Amoah et al., 2020). Coronaviruses can enter wastewater streams via biomedical waste and municipal waste mainly due to related viral particle shedding in human feces and urine (Han et al., 2020; Ling et al., 2020). Such a scenario can lead to the unprecedented spread of this infection and can cause potential contamination of the water system (Parida et al., 2022). In a study conducted by Asano and Levine (1996), a 5-log removal of virus from wastewater streams was reported after chlorinated tertiary treatment of wastewater and so, the significance of wastewater treatment for containing such infections and building a safer society cannot be more emphasized. Chen et al. (2021) stated that primary treatment can remove viruses from wastewater by only directing the settled sludge to digesters, while secondary and tertiary treatments can play a vital role in virus inactivation. In the guidelines published by WHO (2017) for potable reuse of water, it was stated that technologies like microfiltration and ultrafiltration can achieve high efficiency in virus removal.

Wastewater reclamation has been in existence for several decades but an integrated water and wastewater management model has not been adopted till now due to several challenges such as the slow pace in the adoption of wastewater reclamation, spatial abundance of freshwater resources in few regions leading to lack of unified initiatives to cope imminent water crisis, lack of established integrated water resources management framework and guidelines, requirement of differing water quality for different reuse purposes, limited market mechanism for cost recovery from reclaimed water, lack of public awareness about wastewater reuse, and lack of proper scientific researches on the reuse of material and energy, and the effects on soil and water ecosystem (Lyu et al., 2016).

1.3 Integrated Water and Wastewater Management (IWWM)

The term integrated water and wastewater management (IWWM) was first mentioned by the World Bank Group (1998) in the pollution prevention and abatement handbook. As per the report, IWWM is aimed towards protecting freshwater resources, using a systematic approach for planning water utility and managing wastewater generated. Wastewater reclamation in augmentation with IWWM can prove to be an effective tool for addressing the problem of water scarcity (Smol and Koneczna, 2021). Most of the existing wastewater treatment plants (WWTPs) installed across countries are based on the linear economy principle, that is, the take-make-dispose approach (Zhang and Liu, 2022). The water in such a system is derived from the freshwater resources, utilized for different purposes by the community, and then the wastewater generated is treated in the WWTPs for subsequent disposal into the river system. Therefore, the quality of effluent required after the treatment is also of disposal level quality, just so it is safe for release into the natural drainage system.

In the present era of increasingly stressed freshwater resources due to exploding population and urbanization, integrated management of water and wastewater based on circular economy approach can prove beneficial for meeting the humongous water demands (WWAP, 2017). The circular economy approach considers a regenerative system where no material is treated as waste and their utilization is maintained as long as technically, environmentally, and economically feasible (Zhang and Liu, 2022). Since, wastewater has been identified as a potential source of water, developing a circular economy-based model for effective wastewater management as a resource is required, closing the linear human cycle loop starting from source segregation to utilisation (Sgroi et al., 2018). For effective management of resources, there lies the need to identify and assess the crucial factors that are indispensable for the technical, economic, social, environmental, political feasibilities of IWWM system.

1.4 Appropriate Wastewater Treatment Technology (WWTT)

Most countries started emphasizing the treatment of wastewater after the great sanitary awakening in 1930s (Lyu et al., 2016). A sewage treatment plant is a system comprising of all the components that are required for treatment of wastewater, starting from screening of floating materials, removal of grit and sand, sedimentation to remove settleable solids, removal of biological matter through oxidation and reduction, removal or treatment of sludge, tertiary treatment to further improve the quality of effluent and disinfection to remove existing pathogens and to prevent future contamination, therefore, making the effluent safe for future consumption (Peavy et al., 1985). However, most of the STPs installed across the world do not target making water safe for consumption but only safe for disposal into the river system. This approach has led to alarming depletion in the quality of the water in river systems. Due to shrinkage in freshwater availability owing to increasing population and pollution in river system, the objective of installing STPs needs to be changed from just disposal but reutilization. This process of treatment of wastewater to such levels that it becomes suitable for reuse is referred to as reclamation of water. To satisfy the degree of treatment to be given to wastewater to meet the quality and safety levels for reutilization, the technology on which STP is based plays the most important role. Different reuse purposes require different quality levels, and hence not one technology is universally applicable to all, and this led to the concept of appropriate technology. Technology that satisfies the quality and quantity demand of users with optimum resource utilization is deemed appropriate (Kalbar et al. 2013). The concept of appropriate technology was given by economist Schumacher in his book “Small is Beautiful.” As per his philosophy, an appropriate technology will have the potential to serve the desired purpose with no social, economic, or environmental ramifications (Schumacher, 1973). It will be people-centric, local condition-specific, cost-efficient, and sustainable in nature (Akubue, 2000). Several studies have been conducted for the selection of appropriate technology for specific type of wastewaters, e.g., domestic (Kalbar et al., 2012), molasses-based wastewater (Syutsubo et al., 2013), industrial wastewater (Castillo et al., 2017), disinfection technologies selection for reuse (Gomez-Lopez et al., 2009), etc. However, the procedure for the selection of an appropriate technology that suits both the local environment and reuse quality criteria is not yet defined. In India, technology selections are entirely based on past experience and perceived efficiencies of previously installed technologies, thereby, leading to the under-performance of STPs in different local conditions and a huge debt burden on governing agencies (CPCB, 2013).

Several studies have been conducted to obtain the most appropriate treatment technology using different approaches and decision criteria. This underlines how important is the role of appropriate treatment technologies for closing the human-water cycle loop. The benefits of an appropriate treatment technology are as shown in Figure 1.1.

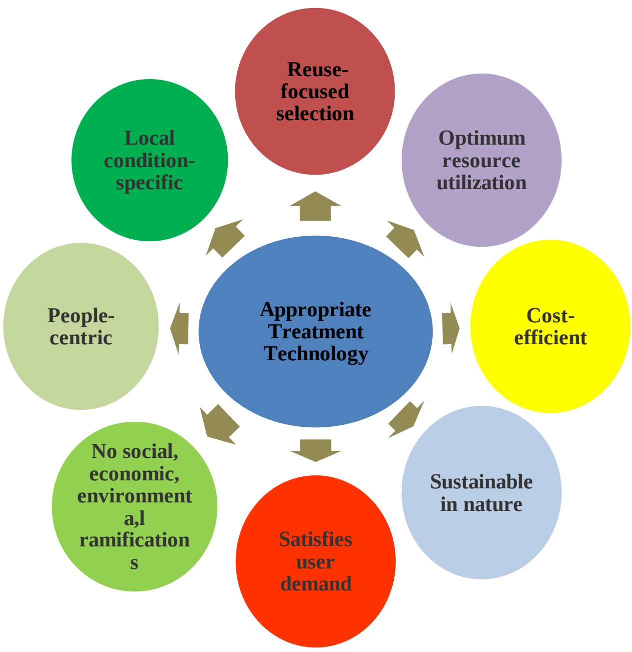

Fig.1.1. The benefits of appropriate treatment technology (Sgroi et al., 2018)

Application of appropriate treatment technologies enables reuse-focused treatment of raw wastewater, that is treatment of available wastewater to the degree required for satisfying quality criteria of the desired purpose. Since quality satisfaction is assured through appropriate treatment, all the resources required for the functioning of STP are estimated and managed efficiently. This also leads to cost-efficiency in the system and assures sustainability of the process. Such a system poses no social, economic, and environmental ramifications but safely satisfies the user demand and is people-centric in nature (Sgroi et al., 2018).

1.5 Decision Support System (DSS)

A Decision Support System (DSS) is an information and communication technology-based software that analyses raw data, organizes them into information, and using models, gives solutions to unstructured problems to feed into decision-making activities (McCosh and Morton, 1978). A DSS provides an optimum solution for a complex scenario consisting of multiple decision criteria. Due to this aspect of integrated problem solving, DSS is being widely adopted (Hamoda et al., 2011). Through DSS, analysis of a problem as a system can be done. The most important characteristics of a DSS are flexibility, ability to analyze information, understand scenarios, user-demand specific, and appropriate solutions and it can be based on four types of methodologies, such as, mathematical models, life cycle assessment, intelligent decision support system, and multi-criteria decision-making (Mannina et al., 2019; Ullah et al., 2020). DSS is being widely employed by the scientific community in studies such as, supporting farmers for agriculture and farming through predictive modeling and simulation scenarios (Kukar et al., 2019), managing water supply for irrigation (Navarro-Hellin et al., 2016; Giusti and Marsili-Libelli, 2015), for assessment of project managers (Naik et al., 2021), equipment selection (Marcher et al., 2019), management of construction and demolition waste (Sobotka and Sagan, 2021), for strategic production allocation (Fadda et al., 2022), for serving the elderly in healthcare (Tang et al., 2019), in textile industry for selection of supplier (Burney and Ali, 2019) and so on.

Application of DSS for appropriate treatment technology selection involves (Hamouda and Anderson, 2009). Since the 1960s, DSSs have been used in wastewater systems to simplify WWTP operation and issues (Anzaldi et al., 2014). DSS based on MCDM in the field of wastewater treatment technology has been deemed to be one of the most reliable methods for effective management of resources. It takes input in the form of data, processes it via appropriate tools and gives output as a solution (Booty et al., 2009).

1.6 Research Issues

A pragmatic shift to the circular economy approach in the water and wastewater sector is required to tackle water scarcity. This requires the creation of reuse-focused integrated water and wastewater management (IWWM) system. Most importantly, if the proper study of critical factors that affect such an IWWM is not undertaken, it will lead to wastage of resources, the underperformance of treatment facilities, bad effluent quality, lower social acceptance, and affect stakeholders' involvement and absence of fundings. There is a need to prioritize the influencing factors and identify the critical interrelationships between them to develop a safe and effective IWWM for wastewater reclamation.

In India, wastewater treatment facilities were not installed for reuse but only for improving the quality of raw wastewater to release the effluent in the river system safely (Tare and Bose, 2009). It is essential to develop a reuse-focused network to safely connect the reclaimed water from sewage treatment plants (STPs) to the consumers (Nemerow et al., 2009). The raw wastewater will be treated to the desired quality standards using appropriate technology and delivered to the reuse site, closing the human water-cycle loop (Sgroi et al., 2019). Numerous wastewater treatment technologies belonging to the primary, secondary, tertiary, and emerging category are available, but a sensitive and reliable methodology for selection of an appropriate technology combination aimed at the reuse of reclaimed water in the local environment based on resource availability of the area is not available.

For setting up a sewage treatment plant, analysis of the demand of reclaimed water in the community is necessary. Demand of reclaimed water for the desired reuse purpose will be a driving factor for setting up STP with appropriate technology and the revenue from selling the reclaimed water will lead to recovery of cost. Therefore, calculation of demand and optimum water price selection is required to cater to the needs of the community without burdening the vulnerable communities.

Addressing these issues will lead to the creation of circular economy in wastewater and water sector, where the water utilized is treated and redistributed to the community for utilization.

1.7 Objectives of the Study

The specific objectives planned for this study are:

a) Identification of reuse purposes and definition of quality criteria
b) Development of a methodology to select appropriate wastewater treatment technology combinations for the desired reuse purposes based on key decision criteria:
    - New STP technology suggestion
    - Upgradation of existing technology
    - Supplementation of existing technology
c) Development of a methodology to allocate reclaimed water to the imposed demands, that is socially and economically viable.
d) Development of a mechanism to calculate the optimum water price for cost-recovery.
e) Development of decision support system (DSS_IWWM) tool that combines all above objectives and provides an ease of application to the government agencies, stakeholders, and engineers.

1.8 Organization of the Thesis

The structure of the thesis is based on the above-defined objectives of obtaining the key influencing factors that affect IWWM towards wastewater reclamation and developing a DSS to aid selection of treatment technology, estimate and allocate reclaimed water demand and obtain sustainable water prices for cost recovery.

After the Chapter 1 on Introduction, Chapter 2 presents the literature review on the different aspects of a reuse focused IWWM, such as, quality criteria for reuse purposes, key factors affecting such a system, wastewater treatment technologies, reuse purpose demands and pricing techniques. The research gaps are also provided at the end of this chapter.

Chapter 3 gives an elaborate representation of the research methodologies adopted for the development of the DSS_IWWM.

Chapter 4 presents the results and discussion part of the developed DSS_IWWM.

Chapter 5 presents the summary and conclusions of the study.