Project Report on

Nutrient and Energy Flows through Natural Treatment Systems

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Authors:

Dr. Pradip Kalbar, Associate Professor, IIT Bombay (Co-PI)

Ms. Shweta Lokhande, Prime Minister's Research Fellow, IIT Bombay

Centre for Urban Science and Engineering

Improving Quality of Urban Life

Indian Institute of Technology Bombay

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1. Background

Urbanization in the 21st century has magnified the challenges of sustainable development. Globally, water crisis is a challenge in terms of quality and quantity, which is attributed to improper water management, inappropriate infrastructure planning and occasional pollution of natural water bodies. The United Nations prioritize clean water and sanitation access under Sustainable Development Goal (SDG) 6. It has become necessary for the governing bodies to invest in social infrastructure i.e., education, health, water supply and sanitation. The enhanced need for clean water has compelled the municipal authorities to search for nearby surface water sources to create water supply infrastructure. The incorporation of life cycle thinking across the continuum of sewerage infrastructure planning is lacking, resulting in several obstacles or failures in achieving sustainable wastewater treatment. Apart from the technical aspects, several governance issues and lack of adequate scientific policies makes it difficult to adequately manage the liquid wastes. A fragmented approach in management prevents the institutions from incorporating newer solutions such as greywater recycling (Leigh and Lee, 2019). To overcome the above-discussed challenges of urban water management, it is imperative to think in a holistic manner as to plan sustainable water supply and wastewater treatment.

1.1. Role of nutrients in ecosystem

Nitrogen is one of the six primary macronutrients required for plants and has to be provided externally as Indian soils are generally devoid of it. Nitrogen supply is reported to strongly affect the crop growth and yields hence nitrogen inputs during fertilizer application are most significant (Möller, 2018). The current practice is of cities importing nutrients from food and materials such as detergents and household chemicals, while only meagre fractions are recovered from the wastewater streams. Humans intake nutrients via food consumed, which get emitted from human bodies as excreta and urine. The nutrients excreted depend on the diet of consumers as well as their digestibility, which decides the nutrient partitioning between urine (comprises digested nutrients) and faeces (undigested nutrients) (Harder et al., 2019). Human excreta have been traditionally used as a fertilizer and as soil amender, however, the widespread use of water closets and underground sewer networks in rapidly urbanizing cities has changed trends to the use of sludge from STPs for fertilizer or manure production. The dried solids from human urine comprise around 13% carbon, 14 to 18% nitrogen and 3.7% phosphorus. In human faeces, the % C, N, P in dry solids range from 5-7%, 3-5.4% and 1 to 2.5% (Harder et al., 2019). As human beings require nutrients for growth, similarly, plants and animals require nutrients for their survival. Figure 1 shows interaction of nitrogen with different life forms.

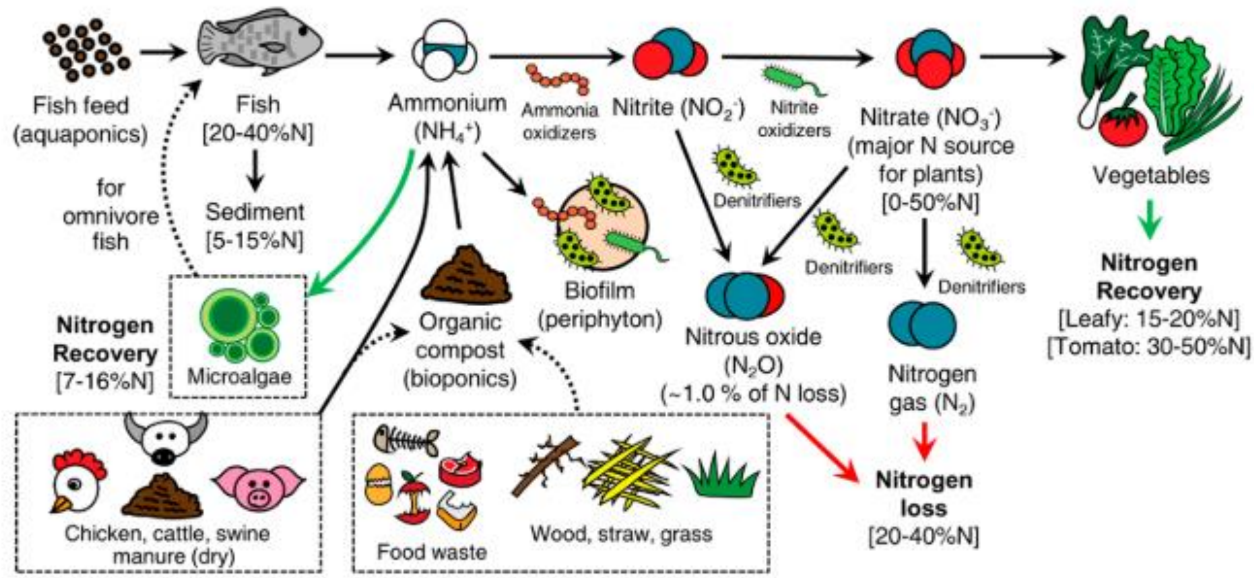


Figure 1: Interaction of nitrogen with different life forms – adopted from Wongkiew et al., (2021)

1.2. Need for nutrient removal and its challenges

The Green Revolution was followed by an increased usage of artificial and inorganic fertilizers. The green revolution in India facilitated use of chemical fertilizers and made the country self-sufficient in the food grain production, however has resulted in several sustainability issues. Nitrogen manufacturing consumes 1-2% of the energy supply worldwide (Batstone et al., 2015), thus fertilizer production is a highly energy-intensive process. NO_2 and N_2O emissions during the life cycle of fertilizers have significantly contributed to climate change. Fertilizers and manures constitute 61% of the total nitrogen as received by agricultural soils globally, the remaining coming from atmospheric deposition, nitrogen fixation etc. (Liu et al., 2020). Further, the subsidized inorganic fertilizers and limited knowledge regarding optimum fertilizer application resulted in an indiscriminate usage by the farmers, and the residual nutrients ultimately found their way into groundwater or went to water bodies as surface runoff (Reddy et al., 2018). Fertilizer production being an energy-consuming process has increased the production cost while the output in terms of yields has stabilized or is only growing marginally (Reddy et al., 2018).

As reported by Mosier et al., (2004), approximately 60% of annual nitrogen consumed in producing food remains unrecovered in usable forms which accumulates in the soil, or gets lost to the environment. The excessive nutrients present in soil, air and water have caused issues such as nitrate pollution, greenhouse gas emissions and eutrophication respectively thereby disturbing the natural N and P cycles (Cui et al., 2021). The excess application of fertilizers worldwide has led to almost 450%, 600% and 250% excess nutrient inputs than the actual crop demand (Wielemaker et al., 2019). Also, the excessive deposition of ammonia from atmosphere has a potential to degrade aquatic and terrestrial ecosystems, which is of concern to agricultural scientists, environmental agencies and policy makers. Thus, the rising demand for inorganic fertilizers is of crucial concern. The limited presence of phosphorus on earth coupled with the nuisance of excess nutrient depositions in soil and in water bodies necessitates for better nutrient management practices.

An undesirable consequence of excess nutrients in water bodies is the emergence of aquatic plants at a growth rate exceeding the ecosystem balance. The over-utilization of phosphorus might exceed the P sorption capacity and lead to increased P runoffs and leaching, also causing eutrophication in surface water bodies. Also, the build-up of nutrients in soils decreases the nutrient use efficiency (Wielemaker et al., 2019). Excess nutrients in water bodies with time resulted in eutrophication in rivers and lakes. Approximately 30 to 40% of the surface water bodies across the world are victims of eutrophication (Reddy et al., 2018). Water hyacinth (WH) has serious consequences with respect to social, environmental and economic problems. An ecological imbalance results in fish kills and death of native aquatic species. WH also provides a habitat for mosquitoes and snails who are vectors of malaria and Schistosomiasis, respectively. The growth of WH affects the navigation and fishing activities, interfere with water supply and treatment, and blocks the water intake structures of hydro-electric plants.

In the wake of growing pollution in aquatic water bodies, the National Green Tribunal (NGT) of India mandated stringent norms for water quality standards, including the nutrients, nitrogen and phosphorus. Removal of WH using mechanical or chemical means often prove to be futile and expensive. Measures such as controlling soil erosion, wastewater treatment and preventing excessive nutrient entry in water bodies are effective and economical ways of controlling the spread of water hyacinth. Nutrient removal comprises the tertiary stage in wastewater treatment and often involves expensive and advanced treatment units. Natural treatment systems are alternative treatment technologies capable of removing substantial quantity of nutrients in a low cost. Hence, it becomes significant to explore the potential of NTS to meet the regulatory norms in an economically feasible manner.

1.3. Need for circular economy in wastewater treatment

In the wake of the stringent norms by the National Green Tribunal in 2019 for nitrogen and phosphorus removal at the STPs, tertiary treatment is desired which requires a significant amount of energy. Instead, the treated wastewater from municipal STPs can be treated affordably using NTS. Moreover, nitrogen in the treated effluent is present in the same form as that in nitrogenous fertilizers produced through energy-intensive industrial processes, hence it has potential to be used in agriculture thereby reducing energy consumption in the production of inorganic fertilizers (Hernández-Chover et al., 2023). This practice will prevent the enormous expenses and energy consumption for removing nutrients from sewage. The use of nutrient-laden treated wastewater for irrigation will also elevate the crop yield, as reported in a few studies.

Several changes from a holistic perspective need to be made in this regard, as depicted in Figure 2. Instead of disposing of domestic sewage in rivers, its usage for non-potable purposes such as irrigation and toilet flushing will reduce the freshwater demand in agriculture. Apart from freshwater scarcity, the European Commission has also listed phosphorus rock as a critical raw material, thus alternative sources of phosphorus are gaining significant (Hernández-Chover et al., 2023). Wastewater treatment facilities should be looked at as factories manufacturing valuable resources in all three forms of liquids, solids, and gases. Incorporating a circular approach for managing wastewater can thus make liquid waste management a sustainable service (Rodriguez et al., 2020). This study has compared the GHG emissions in two scenarios - untreated wastewater being diluted in natural streams vs wastewater reclamation in agriculture, and the reclaimed wastewater scenario was found to reduce the GHG emissions by almost 33% (Miller-Robbie et al., 2017). Moreover, the soil amendments produced by assimilating nutrients from wastewater streams have high organic matter content which positively enhances the soil quality (Wielemaker et al., 2019). Also, increased organic matter enhances the soil porosity which facilitates higher water infiltration and retention rates. This characteristic is useful in retaining water in soils belonging to drought-prone areas and in urban areas which often lack nutrients and organic carbon.

The 6R framework if reduce, reuse, recycle, reclaim, recover and restore, as proposed by Kakwani and Kalbar, (2020) can effectively be applied to achieve water circularity.

Centralized systems lack a holistic planning approach that is desired for future-ready UWI. Shifting to the paradigm of decentralized systems can have substantial benefits in terms of circular economy, recycling and reclamation of wastewater etc. Decentralization is a potential means of overcoming these issues (Kalbar and Lokhande, 2023), and adoption of NTS in a decentralized manner can help gain several economic benefits and attain SDGs.

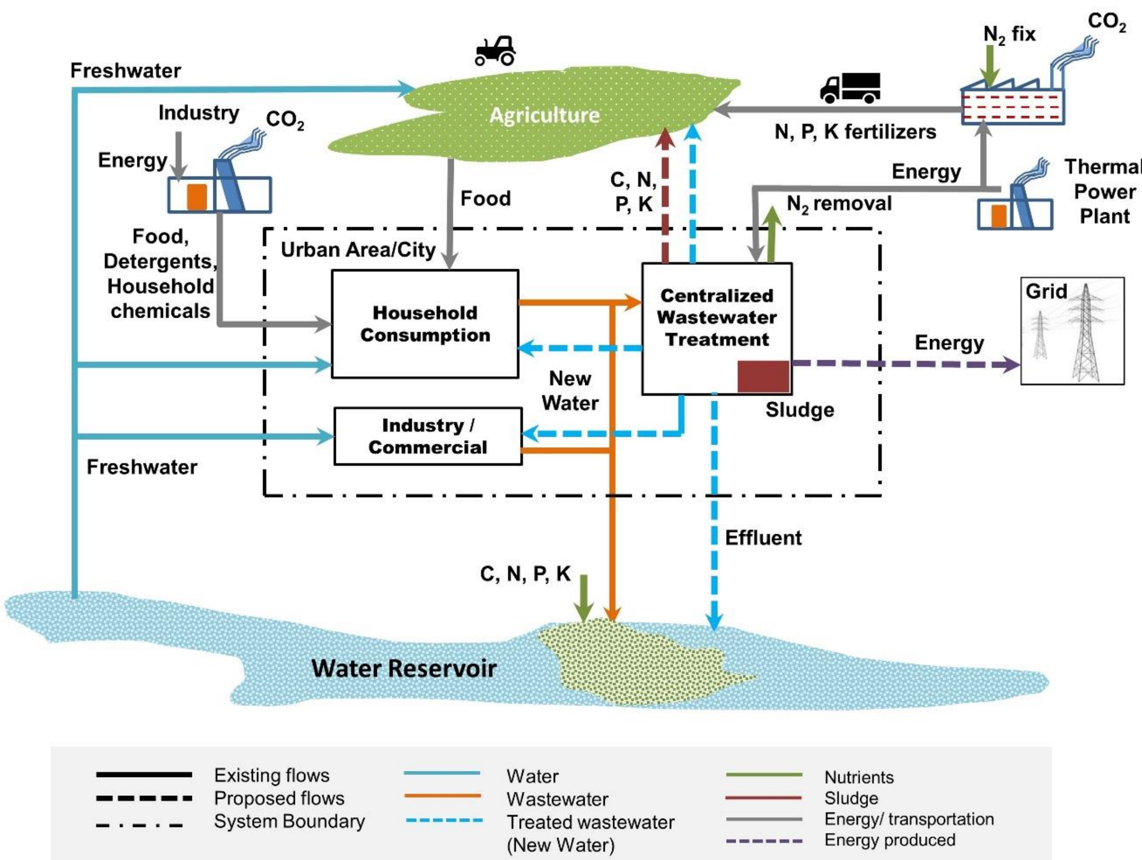


Figure 2: Nutrient flows through a city with centralized infrastructure - adopted from Kalbar and Lokhande, (2023)

2. Natural treatment systems

2.1. Classification

Since times unknown, domestic sewage has been disposed of in the rivers and nearby streams. The water bodies are known to have their self-purification capacities which make them capable of restoring them to their natural form within the course of time despite being polluted by sewage. The oxidation of organic matter present in the sewage takes place improving the water quality of the stream over a specific stretch. The depleted oxygen is simultaneously replenished by natural means by absorption from the atmosphere. However, it is crucial to understand that each river or any other water body has its assimilative capacity due to a fixed rate of replenishment of oxygen from the atmosphere. Hence, the stream or water body gets polluted if it receives pollution load, which it is incapable of treating independently, thereby making the water bodies stressed. Based on this principle, Asolekar et al. (2014) have classified natural aquatic systems as intrinsic or self-sustaining, the detailed classification is shown in Figure 3.

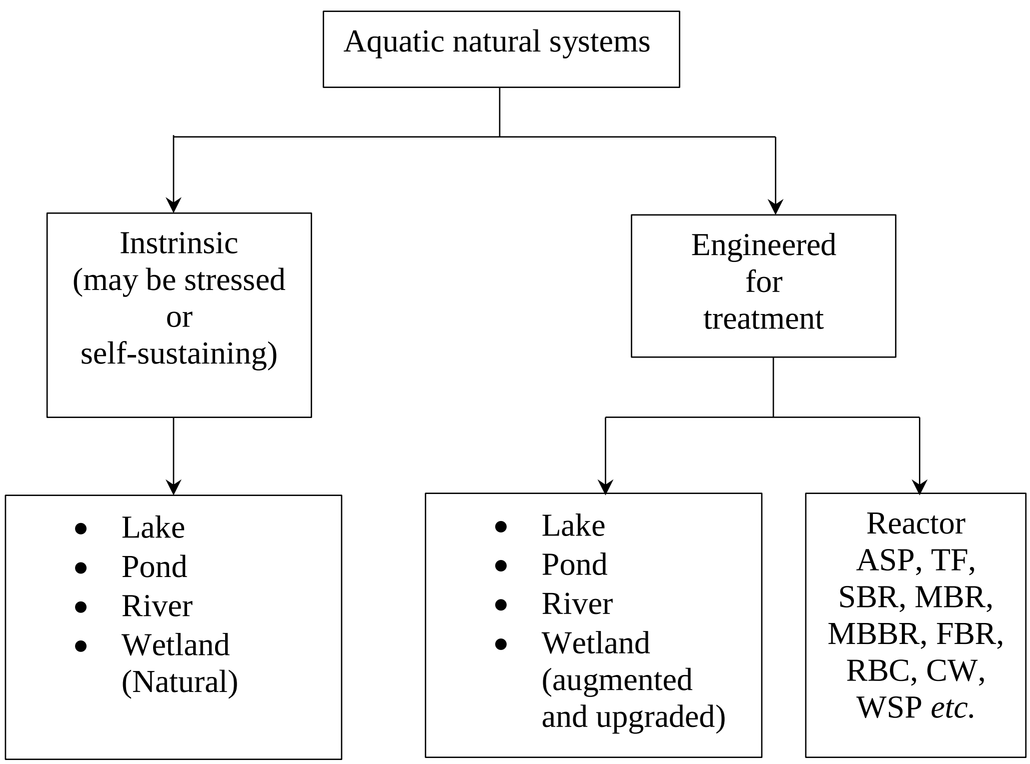


Figure 3: Classification of natural aquatic systems (Asolekar et al., 2014)

Further, the engineered natural treatment systems have broadly been categorized under the heads of systems using phytoremediation (plants); bioremediation (microbes), and zoo-remediation (animals) (Chaturvedi, 2008). This classification is represented in Figure 4. The term 'phyto' means plants. The wastewater treatment systems involving plants for nutrient and metal uptake or those using algae are considered in the 'phytoremediation' section. Further, bioremediation consists of treatment with micro-organisms and bacteria to bring about the oxidation of organic matter. Zoo-remediation involves the treatment of wastewater or conversion of organic waste by animals such as earthworms. It is of utmost importance to maintain the temperature and humidity suitable for the survival of the organisms in these systems.

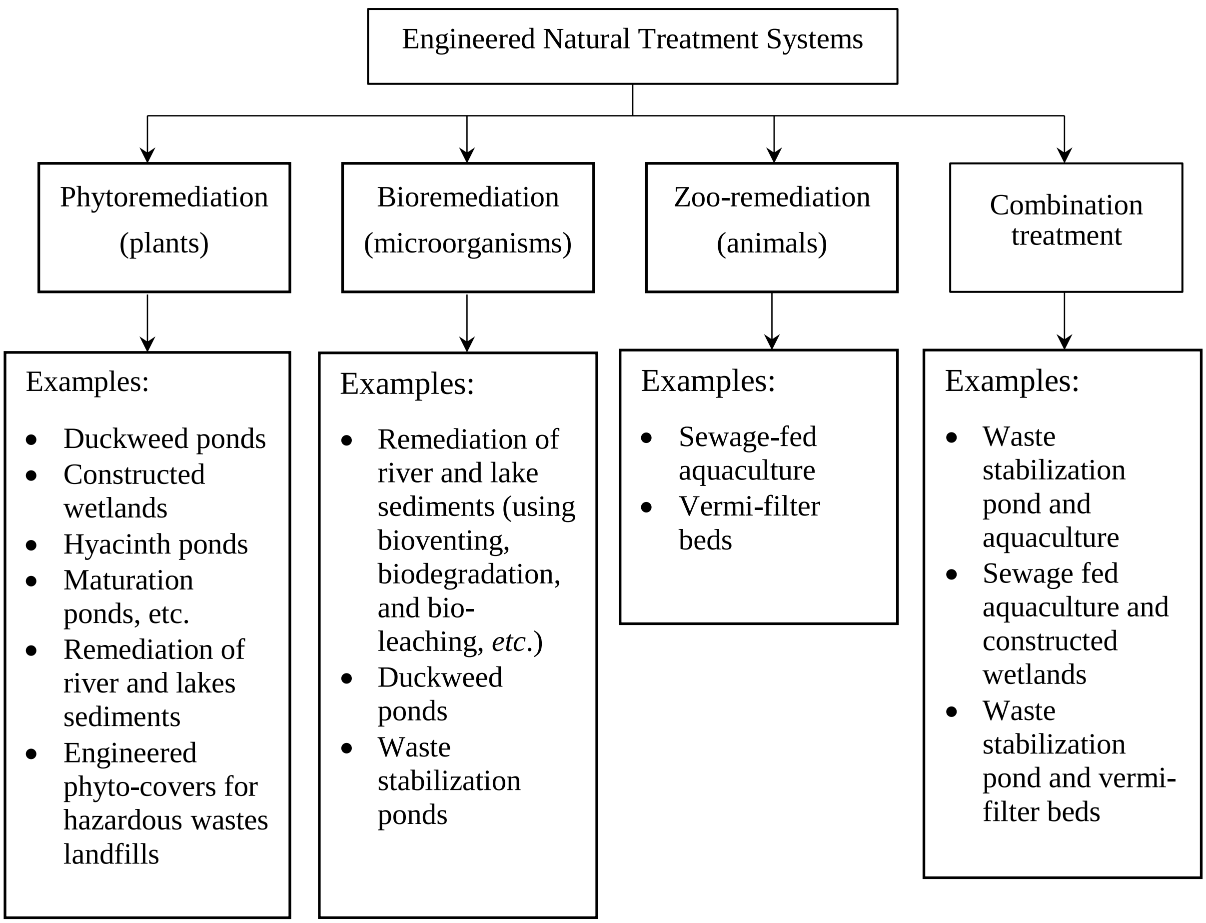


Figure 4: Classification of engineered natural treatment systems (Asolekar et al., 2014)

The engineered systems use pathways similar to those used by natural ecosystems. However, they are engineered, in a way, and rationally designed based on criteria such as hydraulic retention time and surface loading rates to achieve the necessary treatment required to attain the desired quality of effluent. The hydraulic retention time is a significant parameter which ensures sufficient contact time between the microorganisms and wastewater to facilitate the oxidation process. It is vital to ensure the design parameters are maintained during the operational phase of the wastewater treatment to achieve desired results.

2.2. Significance of NTS in implementing circular economy

The expensive wastewater treatment technologies result in sewage treatment being an economic burden on municipal corporations. This problem can be solved by shifting from a linear approach of treating wastewater to dispose of in the surrounding water bodies to a circular approach of extracting materials and energy from the sewage treatment plants and practicing reuse and recycling within the cycle. A circular economy minimizes the waste generation and keeps the products and materials in use for as long as possible. In order to overcome freshwater scarcity, a paradigm shift is required. Wastewater treatment facilities are envisaged as factories manufacturing valuable resources as gases, liquids and solids. Although the circular economy seems to be an attractive solution, it has numerous hurdles for implementation on a large scale. The various challenges in attaining a circular economy in the Indian context have been documented by Kakwani and Kalbar (2020), out of which the technical challenges in wastewater treatment are as follows:

1. Lack of collection infrastructure and maintenance of sewer systems
2. Selection of appropriate technologies
3. Low level of technology readiness; need to assess technology from reliability, robustness, and resilience
4. Emerging contaminants that remain unaddressed by centralized treatment plants
5. Challenges in scaling up lab-scale technologies due to suitability in the Indian context and high costs

The constructed wetland has been found to be the most suitable treatment technology from the perspective of urban reuse due to the advantages of low maintenance costs and low energy requirement. Despite the effluent of constructed wetlands not meeting microbiological standards, they are suitable for reuse in areas not requiring outstanding water quality. One study conducted in Morocco has demonstrated a quicker growth and a higher amount of plant biomass in plots irrigated by treated greywater than those by potable water. The increment of about 60% might be attributed to the nutrient-rich greywater used for irrigation (Laaffat et al., 2019).

Hence, if constructed wetland infrastructure is planned correctly, it has tremendous scope for accomplishing a circular economy. The constructed wetlands effluent can be disinfected and recycled for several non-potable applications such as gardening, toilet flushing, cleaning vehicles, firefighting, *etc.* In this manner, the using treated wastewater will help in reducing freshwater demand. Constructed wetlands in the vicinity of agricultural lands can be used to irrigate the lands. This will reduce the freshwater consumed for agriculture and divert it to other applications; reduce the transportation cost of canals, and decrease the amount of inorganic fertilizers required as nutrients in wastewater will partially suffice the requirement. Moreover, plants used in constructed wetland uptake nitrogen and phosphorus so the harvested plants can be used as fodder for animals. As phosphorus is a limiting nutrient, the recovery of it through wetland plant species is essential.

Further, Ballantine et al. (2010) has conducted a review of potential materials that can be used as substrates in constructed wetlands. This study classifies the substrates as naturally occurring, modified, and processed waste materials. The waste materials analyzed include fly ash, alum from drinking water treatment plants, slag mixtures, *etc*. Thus, waste from thermal power plants, sludge from drinking water treatment plants, construction and demolition waste can actually be reused as substrates in a constructed wetland, thereby reducing the cost of filter media and also reducing the burden on landfill to an extent. The circular economy aspects discussed above are represented in Figure 5.

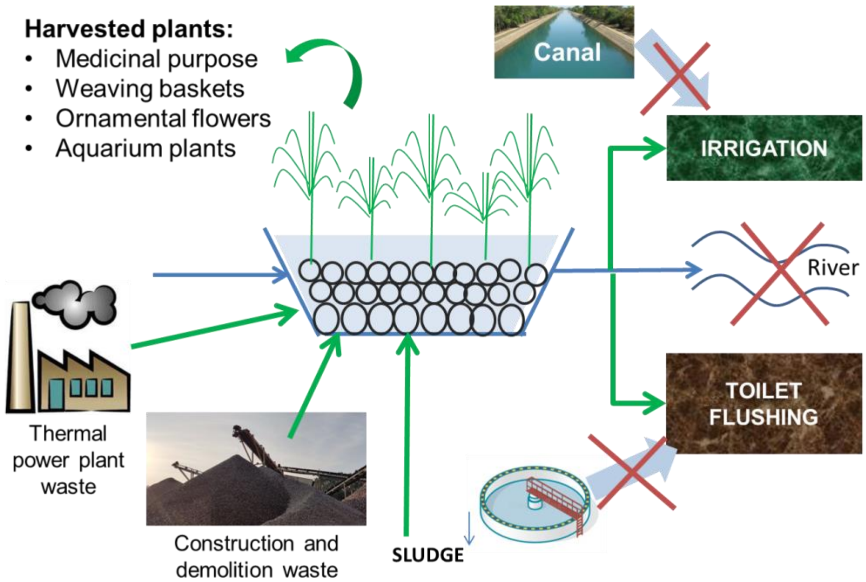


Figure 5: Circular economy aspects using constructed wetlands

2.3. Nutrient cycles

The NTS mimic the natural environment hence an understanding of the nutrient cycles is crucial to understand the transformations occurring within the environment, that can facilitate the effective implementation of NTS.

2.3.1. Nitrogen cycle

The nitrogen transformations are microbial processes and are hence dependent on the presence and absence of microorganisms. The mechanisms occurring differ in aerobic and anaerobic conditions, and are represented in Figure 6 and 7 respectively.

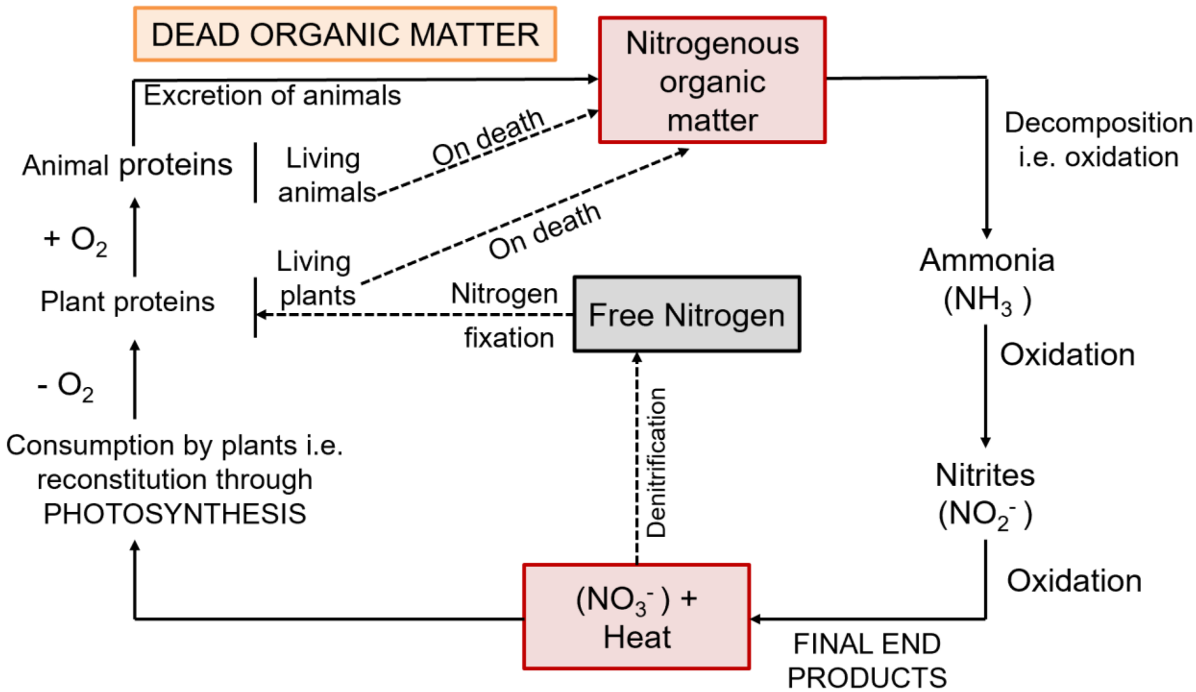


Figure 6: Nitrogen cycle under aerobic oxidation (adapted from S. K. Garg)

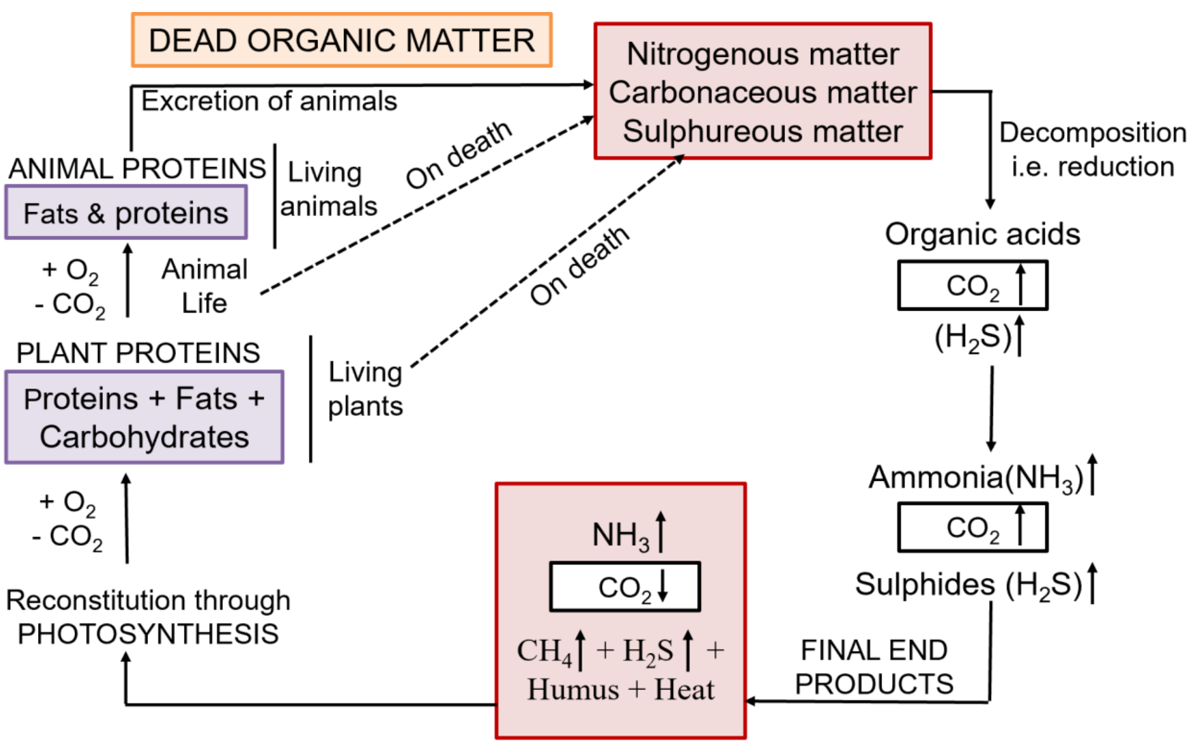


Figure 7: Nitrogen, carbon and sulphur cycles under anaerobic oxidation (adapted from S. K. Garg)

Nitrification and denitrification constitute the pillars of the nitrogen cycle. N in ammonium form (NH_4^+) accepts oxygen and gets converted to nitrite ion (NO_2^-), which upon subsequent acceptance of oxygen gets converted to nitrate (NO_3^-), which is a relatively stable form of N. These reactions are brought out in the presence of nitrifiers, which are the bacteria surviving in aerobic conditions. The conversion of ammonium to nitrite is brought along with Nitrosomonas species while the subsequent conversion of nitrite to nitrates is brought by Nitrobacter. These steps constitute the nitrification. Further, denitrifiers or the heterotrophic bacteria (able to thrive in both anoxic and anaerobic conditions) facilitate the conversion of nitrates to nitrogen gas which is released in the atmosphere. This is done by the pseudomonas or the azotobacter. This step is called as denitrification. The nitrification step is rate limiting due to the need of oxygen for the microbial conversions.

There is another set of bacteria 'Anaerobic Ammonia Oxidation' bacteria, also referred to as annamox bacteria which directly convert to nitrogen form (N_2). Mulder et al., (1995) had reported annamox for the first time, and reported that ammonium oxidation can be brought out in anaerobic conditions using nitrate as electron acceptor and ammonium as the electron donor. Prior to that, oxidation of ammonium was only known to occur under aerobic conditions. Rampuria et al., (2020) have reported the presence of annamox bacteria in deep bed constructed wetland, stating nitrite as the electron acceptor. Mancuso et al., (2021) have recently reported annamox being carried out using either nitrite or nitrate ion.

2.3.2. Carbon cycle

The carbon cycle is depicted in Figure 8. The removal or degradation of organic matter in the form of biochemical oxygen demand typically follows this cycle.

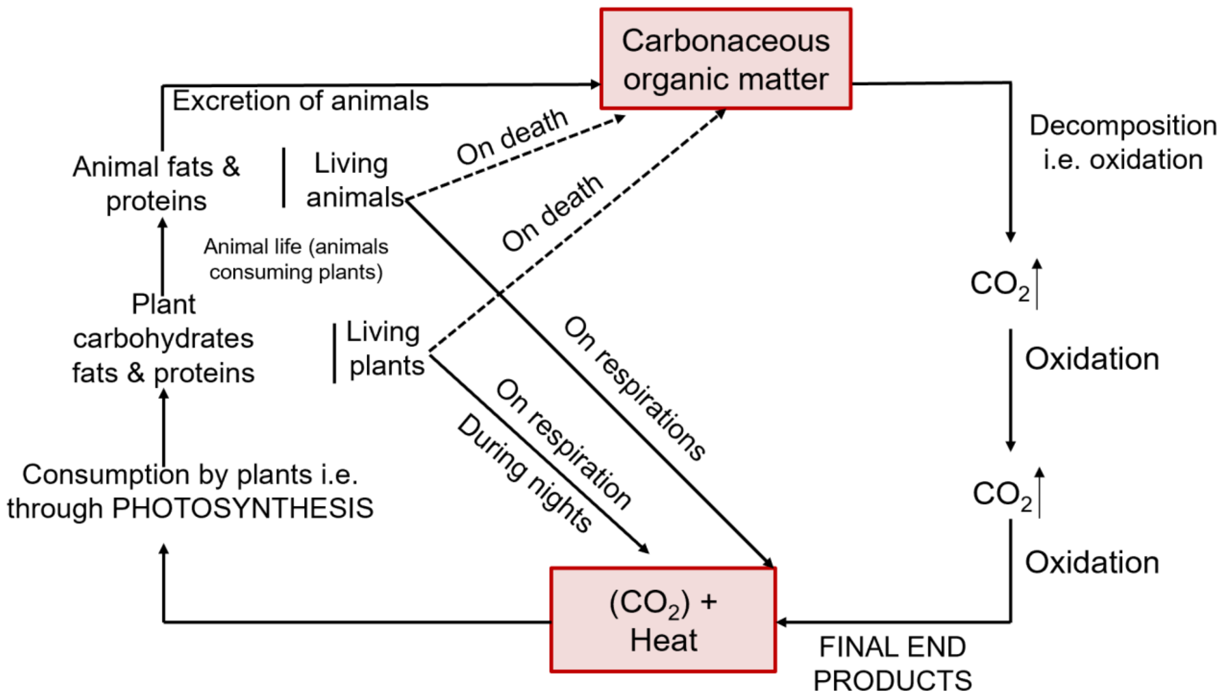


Figure 8: Carbon cycle under aerobic oxidation (adapted from S. K. Garg)

2.3.3. Phosphorus in the environment

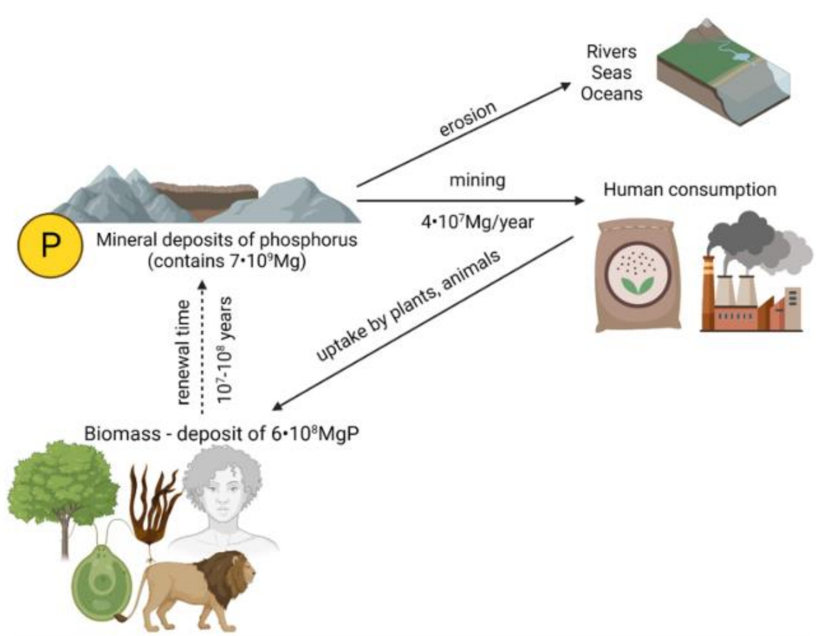


Figure 9: Life cycle of phosphorus mineral - adopted from (Witek-Krowiak et al., 2022)

Phosphorus is not readily available to the plants as it is bound to particles and hence, the demand for P fertilizers is high. In the environment, P is available as inorganic phosphates or organic phosphorus. P has industrial applications as it is used in insecticides, surfactants and plasticizers (Witek-Krowiak et al., 2022). Additionally, phosphorus chlorides are also used to produce pharmaceuticals and electrolytes for individual use. The final form of biological and chemical degradation is orthophosphates. Figure 9 shows the life cycle of P mineral and the interaction between environment, humans and animals.

3. Need for study

In the scenario of nutrient recycling to achieve circular economy, it is vital to assess the current fertilizer usage as well as contribution of wastewater streams in attaining nutrient recycling (Wielemaker et al., 2019). Understanding the nitrogen removal processes in low-cost NTS such as DWPs or WSPs is important for which quantification of ammonia volatization and other nitrogen fluxes is significant. Appropriate and apt knowledge of the various nitrogen fluxes and transformations occurring within the wetland or any pond systems is necessary for proper design of the NTS for pollutant removal or reuse for secondary purposes. If NTS are planned to practice resource recovery, then knowledge of the quantity of biomass or plant waste or other nutrient recovered from the effluents of plant bed is important to plan the usage or transportation of bio-product or any post-processing of the same.

3.1. Research gaps

NTS such as CW, DWP and WSP are dependent on geographic and climatic conditions. The performance is substantially affected by natural parameters and seasonal variation in performance is also a prominent feature of such natural systems. Multiple removal mechanisms simultaneously occur in NTS, an understanding of which becomes crucial to ensure an effective design and optimum performance. Some studies have attempted mass balance models for predicting nitrogen removal from WSPs, DWPs and CWs. However, the validation of the developed models with field studies is needed and more studies across different geographies are also required to understand the performance variation across climatic conditions.

3.2. Objectives

This report aims to study the various mechanisms for pollutant removal across prominent NTS namely constructed wetlands, and pond systems including duckweed ponds and waste stabilization ponds. Further, the performance efficiency of the NTS is also discussed in terms of in nutrient removal as reported in various studies. The objectives of this work are as follows:

1. To assess the potential of NTS in attaining circular economy of nutrients
2. To study pathways of nutrient removal in NTS
3. To analyze nutrient flows for possible resource recovery from NTS

4. Nutrient flows

The resource flows occur at differing spatio-temporal scales with each scale being associated with its own boundaries, flows and activities. The efficiency of resource flows occurring within a system is a function of scale, local conditions, technologies, urban pattern and characteristics (Agudelo-Vera et al., 2012). To make the best utilization of resources and prevent wastage or losses, it is crucial to understand the system through which a particular resource flow. Material flow analysis is one prominent methods of sustainability assessment which helps to map the flows across any system within a boundary. It is discussed in the sub-section below, followed by the applications of the same for nutrient mapping or analysis as reported in literature.

4.1. Material Flow Analysis (MFA)

Material Flow Analysis (MFA) is regarded as a useful tool in waste management, nutrient management in agriculture, and resource recovery studies. The modelling of nutrient and water and wastewater flows in an urban area highlight the risks posed to the environment and can serve as a medium to link sanitation with agricultural production and resource recovery (Meinzinger et al., 2009). Additionally, MFA is also suitable to assess the resource use and environmental impact of various sanitation cases. For example, scenario analysis has shown that excess nitrogen is provided by recycling products which can be used to fertilize additional areas in the adjacent town borders (Meinzinger et al., 2009). Although several resource recycling facilities have been proposed for sustainable sanitation, they need to be appropriately embedded in the systems for which understanding the current and future material flows around urban areas is significant. Further, nutrient recovery is an important advantage of natural treatment systems and the application of MFA for assessing the potential of nutrient recovery is significant.

Material flow analysis is one of the tools for assessing the sustainability of urban systems. It is a systematic assessment of stocks and flows in a defined time and space. The term material stands for both substances and goods. Substance denotes a single element for example nitrogen or phosphorus. Goods indicates a combination of substances for example fertilizers can be regarded as goods as they comprise of multiple elements and chemicals in a fixed proportion. The mass flow of substances is assessed in a given system boundary comprising of flows and processes. The mass flows occurring within different processes are modelled through transfer coefficients that describe the partitioning of substances in the process. Replicating the mass balance of real-world systems is exhaustive, data intensive, time consuming and often impossible. Hence, certain indicator elements are used for representative analysis and those serve as a means of achieving maximum information with minimum effort.

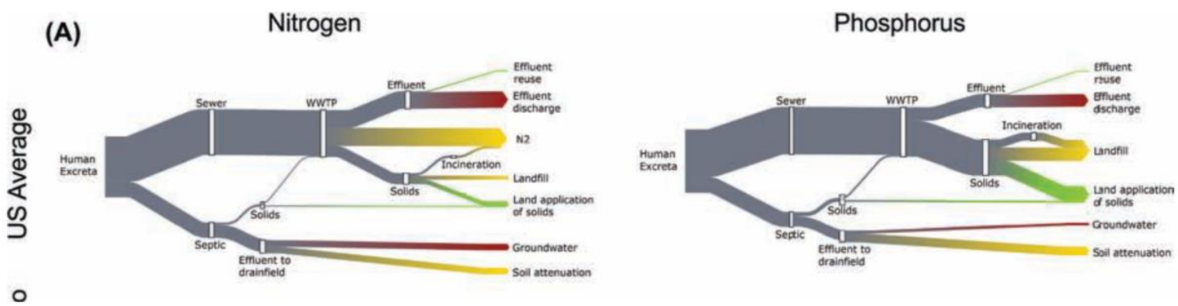


Figure 10: Sankey diagram illustration (adopted from Cease et al., 2015)

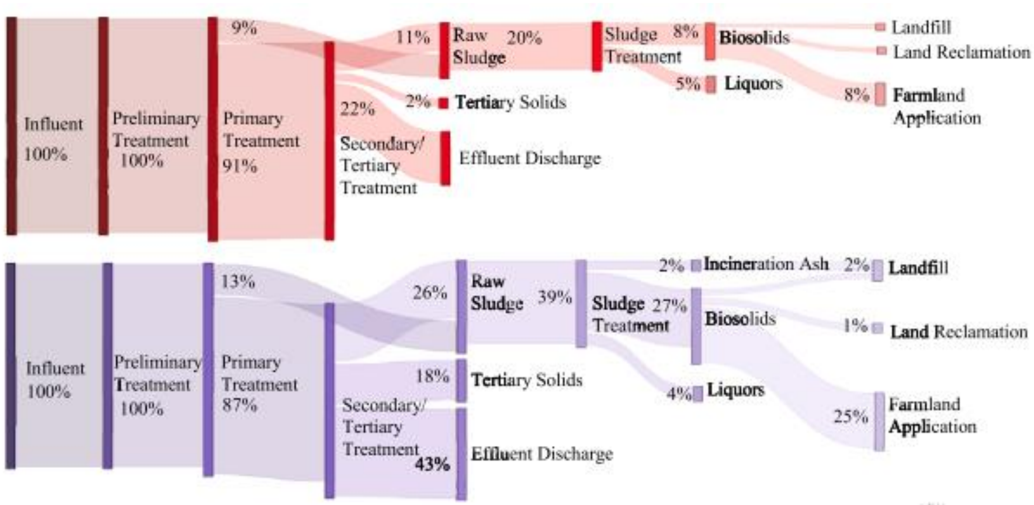


Figure 11: Sankey diagrams showing fate of substances in a wastewater system - adopted from Renfrew et al., (2022)

The mass balances for MFAs are often represented using Sankey diagrams as shown in Figure 10 and Figure 11. The characteristic of these diagrams is that their thickness is proportional to the magnitude of flow, hence depicting a clear visual representation of flows across the system boundary. This representation helps in identifying those processes that are critical and focus on taking measures accordingly.

4.2. Applications of MFA

STAN is a popular software used to model Sankey diagrams. It helps the user work in multiple layers, create the flow diagrams in the software itself and also facilitates uncertainty analysis. The ecological footprints of cities are known to overshoot their biocapacities by almost 15-150 times which is indicative of their high dependence on other cities and hinterlands for energy and material supply as well as waste disposal (Agudelo-Vera et al., 2012). This shows the unsustainable nature of current urban development and water management practices. The large imbalance in nutrient flows in cities necessitates the adoption of a circular metabolism approach for sustainable resource consumption. In the wake of water crisis, agriculture which is the bulk water consumer (consuming almost 80% water) might be drastically affected due to the possibility of water being diverted to more productive sectors. Hence, amidst the global freshwater scarcity, recycled wastewater has become a potential alternative source for agriculture in the arid and semi-arid countries. Reusing treated wastewater in agricultural (fertilizer replacement with nutrient-laden wastewater) and urban applications such as landscape irrigation has economic and environmental advantages. Using treated wastewater for agriculture and irrigation has been reported to be largest reuse option (Almuktar et al., 2018). The use of reclaimed wastewater for irrigation was suggested rather than the sole dependency on existing water resources (Ham et al., 2007). Further, the Urban Harvest concept is based on urban metabolism and is used to close the urban cycles by harvesting resources. Agudelo-Vera et al. (2012) have quantified the potential of harvesting energy and water at various scales.

Material flow analysis can be useful in analyzing the above solutions and quantifying the environmental benefits of various alternatives. MFA has been used as a decision-making tool for choice of technology in the strategic sanitation plans (Yiougo et al., 2011). For example, it was shown that despite the wastewater technologies improving health in the short term, it has elevated the pollution levels of nitrogen flows by 7.4% in the groundwater in the medium term. Another study has reported almost 57% reduction in the chemical fertilizer requirement by the use of treated wastewater for peri-urban agriculture (Yiougo et al., 2011). For the efficient use of MFA in developing countries, models involving only the challenging processes and flows should be used (Yiougo et al., 2011). Such simper models facilitate data collection as well as use and interpretation by local experts. Further, combining MFA with economic analysis including capital cost, O&M cost and willingness of households to pay allows informed choices for sustainable liquid waste management options (Yiougo et al., 2011). Changes in sewerage systems also require changes in logistics for example transportation and storage of organic wastes, compost, urine and other recycled products (Meinzinger et al., 2009).

With regard to natural treatment systems, the nutrient removal capacity is dependent on the pretreatment, influent load received and wetland characteristics such as organic matter content, hydraulic efficiency depending on design depth and vegetation (Andersson et al., 1996). To adopt the NTS for a particular beneficiary use, especially for tertiary treatment or nutrient recovery, it is vital to understand the pathways of nutrient removal in the NTS variants. Hence, an in-depth understanding of the parameter removal mechanisms in NTS will be used to develop a framework to assess the potential of NTS for resource recovery. The implications of seasonal variations on the performance of NTS will be analyzed and conditions favouring nutrient removal will be assessed to maximize the nutrient recovery potential of NTS.

5. Constructed wetlands

Constructed wetlands are the most popular form of NTS globally as well as in India. They are capable of improving the water quality as well as enhancing the biodiversity in a region, thus making it an attractive option for urban planners (Nandkumar et al., 2019). Some essential definitions on phytoremediation, particularly constructed wetlands, are listed below:

1. "Phytoremediation can be defined as the use of plant techniques to remove or degrade organic and inorganic metal constituent present in soil and water." (Mathur and Mathur, 2019)
2. "Constructed wetlands (CWs) are artificial developed engineered systems which are formulated and constructed to operate the natural processes like vegetative wetlands, natural soils, with connected microbial assemblages helps in treating wastewaters by the action of filtration, adsorption, sedimentation and phytoremediation" (Sudarshan and Srihari, 2019)
3. "CW is a unit that consists of large tanks/ artificial ponds with porous media beds planted with aquatic emergent macrophytes and other plants adapted to saturated conditions through which wastewater is passed either in horizontal or vertical mode." (Koli and Munavalli, 2021)
4. "Constructed wetlands are engineered systems artificially developed to function natural processes along with coexisting microorganisms to aid wastewater treatment. The wetland vegetation and the microbial population present in media are the key functional units in constructed wetlands whose natural mechanisms assist in removal of the contaminants present in groundwater or surface water." (Sudrashan and Srihari, 2019)
5. "The treatment process employing constructed wetlands is an engineered, artificial process based mainly on the principal of degradation of organic and inorganic pollutants available in wastewater by oxidation in gravel media with the aid of pump mechanism of supply of oxygen through the stem and root network of the vegetation along with few other ancillary mechanisms like adsorption, filtration acting as facilitators by providing localized sites of degradation." (Joshi and Harne, 2010)

The wastewater treatment in a constructed wetland occurs due to an interaction between various zones such as the sediments, media pores, plant and plant roots, biomass zones associated with plants as well as media. An in-depth understanding of the removal mechanisms of various parameters is vital to develop performance prediction models. The carbon and nutrient cycles are the basis of constituent transformations occurring in the wetlands and aquatic systems. Since the aerobic as well as anaerobic conditions, co-exist in wetland systems, both the carbon as well as nutrient cycles are operative. However, the relative contribution of both cycles varies throughout the year and is difficult to predict.

5.1. Constructed wetland configurations

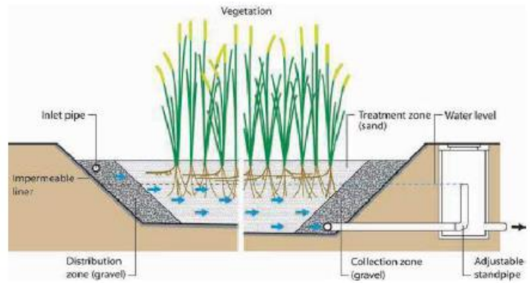
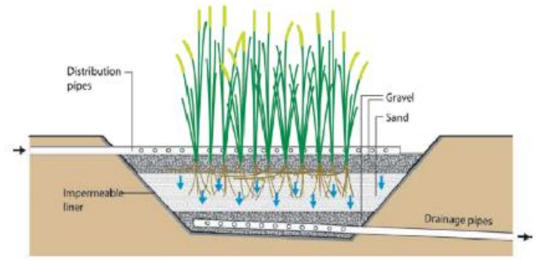
Constructed wetlands are mainly classified as per the flow direction and secondly according to wastewater level with respect to the ground level. Another emerging variant of constructed wetlands is the floating wetlands which is basically a wetland in aquatic ponds or water bodies. The basic mechanisms by which contaminants get removed remain the same in these wetland configurations; however, the efficiency of parameter removal changes. Additionally, there are several variants of CWs emerging to account for land constraints especially in cold regions and urban areas. Deep bed wetlands, aerated wetlands, baffled wetlands, variation in plant species or substrate materials or hybrid wetlands are being used and explored by researchers. The two basic wetland configurations are described below.

5.1.1. Horizontal and vertical flow

There are two flow patterns commonly used in wetlands, depending on the flow directions of wastewater, namely horizontal and vertical flow. The characteristics of both flow patterns are summarized in Table 1:

Table 1: Comparison of horizontal and vertical flow wetlands

Sr. No	Horizontal flow	Vertical flow
1	Limited oxygen supply	Sufficient oxygen supply
2	Enhanced nitrification is not achieved	Almost complete nitrification achieved
3	Efficient denitrification	Nitrogen remains in the form of nitrate

4		
	Source of figures: (Hoffmann et al., 2011)	

It is suggested by Goswami et al. (2019) to operate the vertical and horizontal flow wetlands in batch and continuous mode, respectively. The distribution of roots in the case of horizontal flow wetland needs to be maintained uniformly throughout the filter bed height. Still, in the case of vertical flow wetland, it is vital to ensure the uniform root distribution only in the upper layers (top 10 cm). The use of HSSF CW has advantages of attractive biomass yield and also compensates for the evapotranspiration losses (Barbagallo et al., 2014). The higher oxygen transfer capacity in vertical wetlands, efficient nitrification, and BOD removal has led to a growing interest in the same (Hoffmann et al., 2011). However, lesser efficiency of solids removal might lead to early clogging of the system. The limitations of both vertical and horizontal configurations have led to the concept of hybrid wetlands consisting of both horizontal and vertical wetland is series. The nitrogen can be nitrified entirely in the initial vertical flow CW whereas it can subsequently be denitrified in the succeeding horizontal CW (Ramprasad et al., 2017).

5.1.2. Free surface and sub-surface CWs

Based on the level of water flow, wetlands are classified as free water surface and subsurface flow constructed wetlands, as shown in Figure 12.

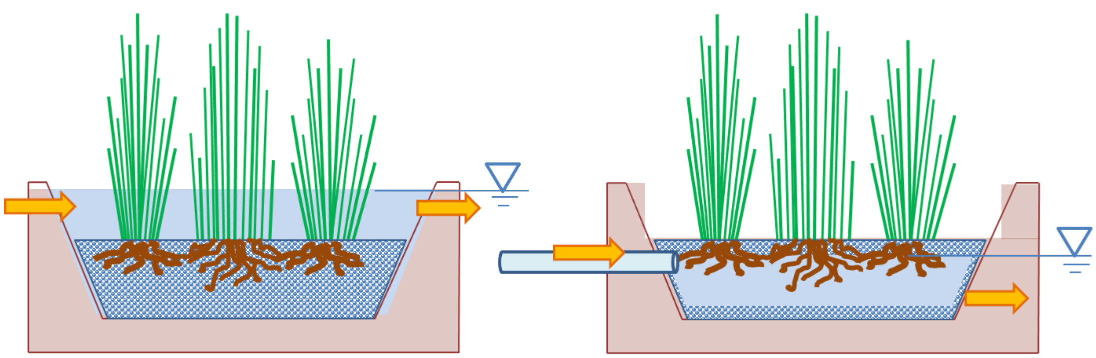


Figure 12: Free surface (left) and subsurface wetlands (right)

Free water surface CW:

Surface flow or free water surface flow CW has partial wastewater flow through leaves and stems that may encourage algal production, odors, and mosquito breeding. The stems and submerged leaves in wetland, to an extent, serve as media supporting bacterial growth. The leaves shade the water surface preventing algal growth to some extent. However, the algal growth is inevitable and results in early clogging of the system. The oxygen traverses from the leaves to roots, thereby supporting the growth of plants. The suggested pre-treatment for these wetlands is rotary disc filters, imhoff tanks, septic tanks, or stabilization lagoons.

Sub-surface flow CW:

Sub-surface flow has a higher wastewater flow area, so less land is needed, making it suitable for urban neighborhoods (Goswami et al., 2019). Sub-surface CWs are less sensitive to extreme winter conditions of frost and snow and have a considerably lesser foul odor, mosquitoes, and algal formation problems, thus facilitating its universal adoption all over the world compared to surface flow CW (Khalil, 2017). However, the increased cost due to gravel media and construction volume are the disadvantages of these systems.

Free water surface flow wetlands require lower capital costs than sub-surface wetlands as the cost of media is limited to the bottom of the beds only (Almuktar et al., 2018). Unlike free water surface CW, sub-surface wetlands do not have any exposed water surface. The wastewater being protected from the effect of wind currents and re-suspension thus enables an effluent with a lower concentration of suspended solids. Also, the evaporation rates are low for sub-surface wetlands. The sub-surface flow systems fail if they receive algal-loaded wastewater from a facultative pond. The trapping of algae at the inlet and further decomposition of it adds to the organic load.

5.2. Removal mechanisms

The removal of contaminants takes place through a combination of mechanisms, namely: sedimentation, precipitation, adsorption, filtration, plant uptake, cation exchange, oxidation-reduction, bacterial degradation, *etc.* CPCB, (2019) categorizes the various wetland mechanisms as physical, chemical and biological processes. The physical processes include sedimentation, and is majorly responsible for reducing the organic load. The chemical processes comprise of adsorption, chelation and precipitation, with phosphorus and heavy metals being primarily removed through these processes. Finally, the biological processes such as nitrification, denitrification and ammonification are dependent on microorganisms and oxygen availability, and nitrogen transformations majorly associated with these processes. Table 2 below lists the mechanisms by which individual parameters get removed. Further, Table 3 shows the removal pathways of various forms of nitrogen and phosphorus as reported by various studies. Figure 13 below illustrates the details of mechanisms contributing to the removal of a particular pollutant.

Table 2: Pollutant removal mechanisms in the constructed wetland (Crites et al., 2010)

Sr. No	Pollutant	Removal Mechanisms
1	Biodegradable organics	Bioconversion by facultative and anaerobic bacteria on plant and debris surfaces
2	Suspended solids	Filtration, sedimentation
3	Nitrogen	Nitrification-denitrification, plant uptake, volatilization
4	Phosphorus	Filtration, sedimentation, plant uptake
5	Heavy metals	Adsorption of plant roots and debris surfaces, sedimentation
6	Trace organics	Adsorption, biodegradation
7	Pathogens	Natural decay, predation, sedimentation, excretion of antibiotics from plant roots

Table 3: Suggested nutrient removal mechanisms in literature

Parameter	Bioconversion/ bacterial degradation	Plant uptake/ Plant assimilation	Nitrification-denitrification	Sedimentation	Adsorption	Chemical Precipitation	Mineralization
TN	Rampuria et al., 2020	Rampuria et al., 2020	Rampuria et al., 2020	Rampuria et al., 2020			Rampuria et al., 2020
TP	Vymazal, 2007	Kamilya et al., 2022 Vymazal, 2007			Kamilya et al., 2022 Vymazal, 2007 Drizo et al., 1999	Vymazal, 2007 Drizo et al., 1999	
TKN		Ayaz and Acka, 2001	Ayaz and Acka, 2001				
Nitrate		Chen et al. 2009					

Phosphate		Kadlec and Knight 1996			Kadlec and Knight 1996		

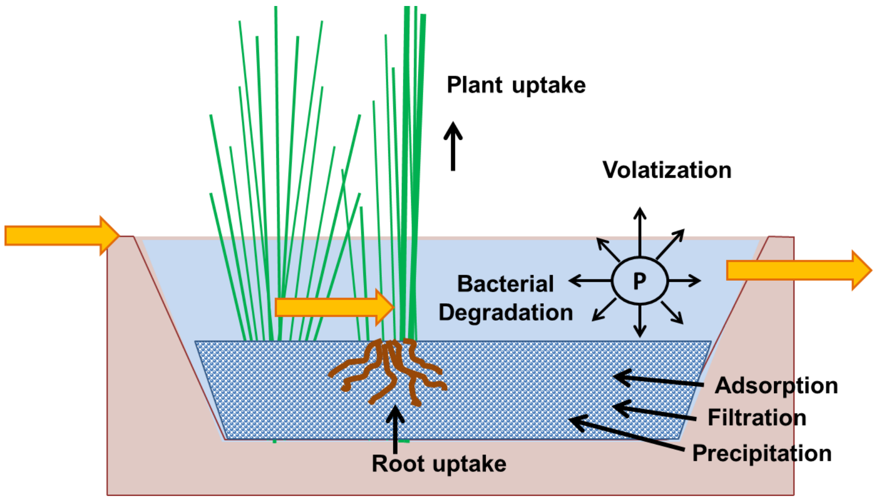


Figure 13: Illustration of removal mechanisms occurring in a constructed wetland

5.2.1. Physical processes

The kinetics and mechanisms associated with the removal of soluble, particulate, and colloidal solids are different. Due to multi-size particles, the modeling of BOD (Biochemical Oxygen Demand) and TSS (Total Suspended Solids) becomes complicated. The BOD removal rate constant is known to vary as the wastewater flows across the wetland, adding to the complexity of modeling. The removal of larger particles (by flocculation, sedimentation, straining, and entrapment) affects the removal rate of smaller particles and results in decreased removal rate coefficient. Sediments having a hydraulic conductivity of 12-15 m/d, comprising of medium to coarse grain soil and 30-39% porosity, are reported to be of potential use in wetlands (Sonkamble et al., 2018).

Wetland hydraulics plays a significant role in the treatment. The possibility of phosphorus precipitation in a wetland was reported due to the residues of chemicals used during wastewater treatment (Andersson et al., 1996).

Fluids can flow through a porous medium due to pressure difference, kinetic energy, potential energy or surface tension. Soil can be considered as a porous medium where water flow is driven by the gravitational potential difference. The vertical transmission of water through a bed is largely dependent on the hydraulic conductivity of the soil, which depends on the soil matric potential i.e.

the ability of the soil matrix to hold the water. The matric potential is the main driving force for infiltration in horizontal flows, as the gravity potential tends to zero (Dufay, 1998).

5.2.2. Chemical processes

The mineral soils in wetland are reported to have a higher P retention capacity than the organic soils. Adsorption of phosphorus on the mineral sediments is an important removal mechanism. The biogeochemical cycles of P are closely associated with the organic matter in sediments (Jin et al., 2013).

5.2.3. Biological processes

The vegetation in a wetland has a dense matrix of roots which provides a surface to shelter a diverse variety of microorganisms at the bottom. The presence of arenchyma tissues which are air-filled, allows the plants to grow in anoxic and anaerobic soil conditions and, despite that provide oxygen to the root structures. The plant roots enhance the hydraulic conductivity of the wetland, aid in velocity reduction and filtration (Koli and Munavalli, 2021). Wetland plants have a unique coping strategy to operate in an anaerobic environment. The widespread aerenchyma tissue formed provides low resistance to oxygen, enabling it to pass from aerial parts of plants to the roots. Constructed wetlands surpass the conventional technologies in this regard and can remove metals without substantial costs and energy (Rana and Maiti, 2018).

Heterotrophic denitrification is a microbial remedial pathway for converting nitrate to nitrogen gas occurring through a series of enzymatic reactions. The organic carbon is used as an electron and energy donor under reduced conditions. This approach is simple, cost-effective, and highly efficient, thereby causing insignificant pollution. Thus, introducing an external carbon source in a wetland is regarded as an effective way of removing nitrate (Chang et al., 2018). The oxidation of organic matter by reducing sulphate to hydrogen sulphide by sulphur reducing bacteria is the primary pathway for sulphate removal (Singh and Chakraborty, 2020).

As far as nutrients are concerned, ecosystem characteristics such as plant species used and their growth pattern affect the performance of nutrient removal. Thus, temperature solely cannot account for seasonal changes. The composition of plant community and their growth dynamics indirectly impact the physical and chemical environment prevalent in a wetland due to processes such as decomposition, photosynthesis, and biomass death (Andersson et al., 1996). The removal of (NO_3 +NO_2)-N was observed to be dependent on the temperature and hence was higher during warmer months than the colder time periods (Chavan et al., 2008).

Nitrification/denitrification is a major mechanisms for nitrogen removal in wetlands, the other two significant ones are ammonia volatilization and plant uptake (Lim et al., 2001). The nitrogen transformation occurs in the oxidized and reduced layers of the media, at the root-soil interface and within the submerged portion of the emergent plants (Lim et al., 2001). At the interface of the roots and soil, the wetland plants transfer atmospheric oxygen to the root zone and create an aerobic layer similar to that which exists at the interface of media-water and media-air (Lim et al., 2001).

The ammoniacal nitrogen is oxidized to nitrate during nitrification process occurring in the aerobic rhizosphere. The nitrate either diffuses into the reduced zone where it is converted to nitrogen or nitrous oxide by denitrification, or it is taken up by the plants. The vegetated wetlands thus outperform the unvegetated wetlands with regard to nitrogen removal due to this involvement of plants in the removal process (Lim et al., 2001) or due to root-zone reaeration by the plants (Chavan et al., 2008). In case of FWS, a shallow water level exists above the media where algal photosynthesis and nitrification occurs. Elevated pH exceeding 10 due to algal phosynthesis during daytime favours ammonia removal by volatization (Lim et al., 2001).

The harvesting of biomass at regular intervals has shown to improve the overall nitrogen removal efficiency of the wetland. A harvesting frequency of 8 weeks has resulted in maximum of 86% N removal with the plant uptake rate of 7.1±7.5 kg/ha/day (Lim et al., 2001).

The nitrogen speciation as well as influent loadings of nitrate-nitrite influence the nitrogen removal in a wetland (Chavan et al., 2008). As against plant uptake, bacterial denitrification dominates the nitrogen removal in FWS CWs (Chavan et al., 2008). Denitrification depends on the prevailing concentrations of DO, NO_3-N, organic carbon, as well as environmental conditions such as pH and temperature. The NO_3-N was reported to be positively correlated with temperature (Chavan et al., 2008).

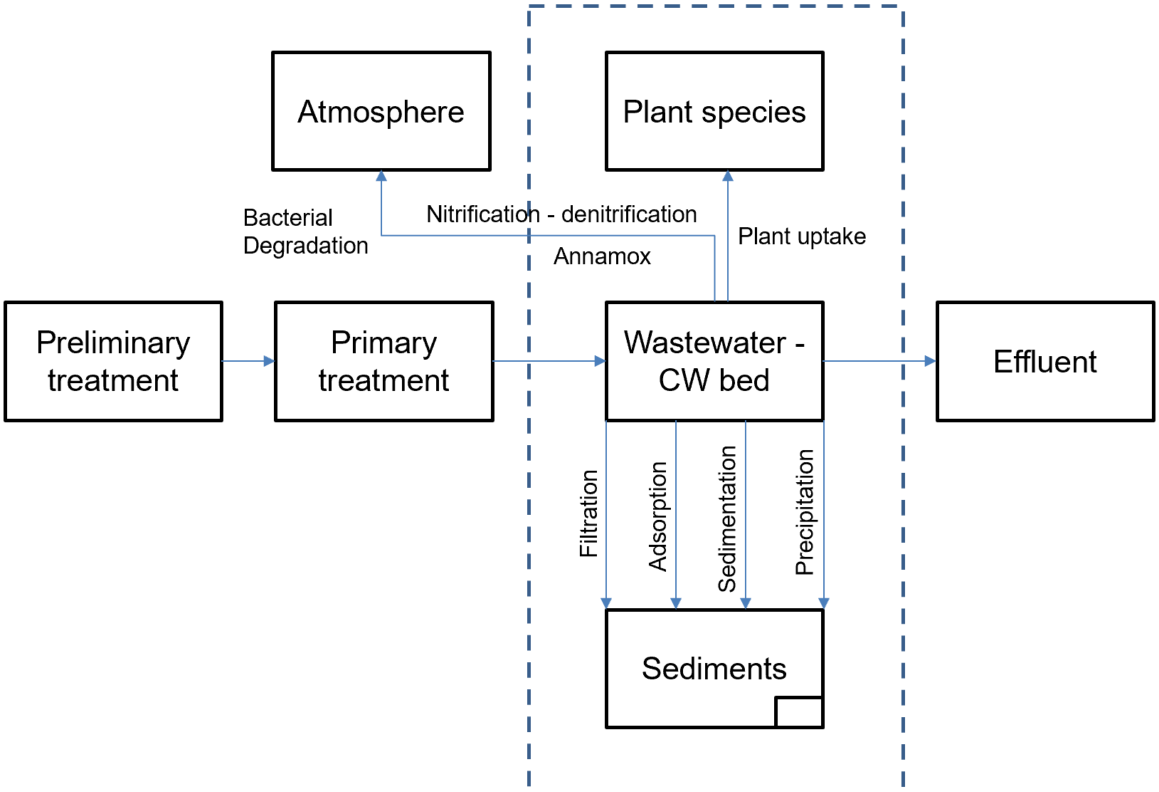


Figure 14: Transformations taking place in a CW bed

The transformations taking place in a CW bed are depicted in Figure 14. Typically, NTS such as CWs function adequately with primary treatment. The effluent after primary treatment units then enters the wetland bed where a mix of mechanisms occur simultaneously. The substrate of wetland bed comprises of sediments, gravel and soil with which the associated mechanisms are filtration, adsorption, sedimentation and precipitation. The CW plants also have a role to play in the plant uptake, with varying rates for different plant species. Simultaneously, microbial processes such as assimilation, bacterial degradation also take place. Nitrification-denitrification and annamox are also pathways for nutrient removal or transformations, which release nitrogen in the atmosphere. After the cumulative effect on influent nitrogen, the remainder flows in the effluent.

5.3. Pathways for nutrient removal in deep bed CWs

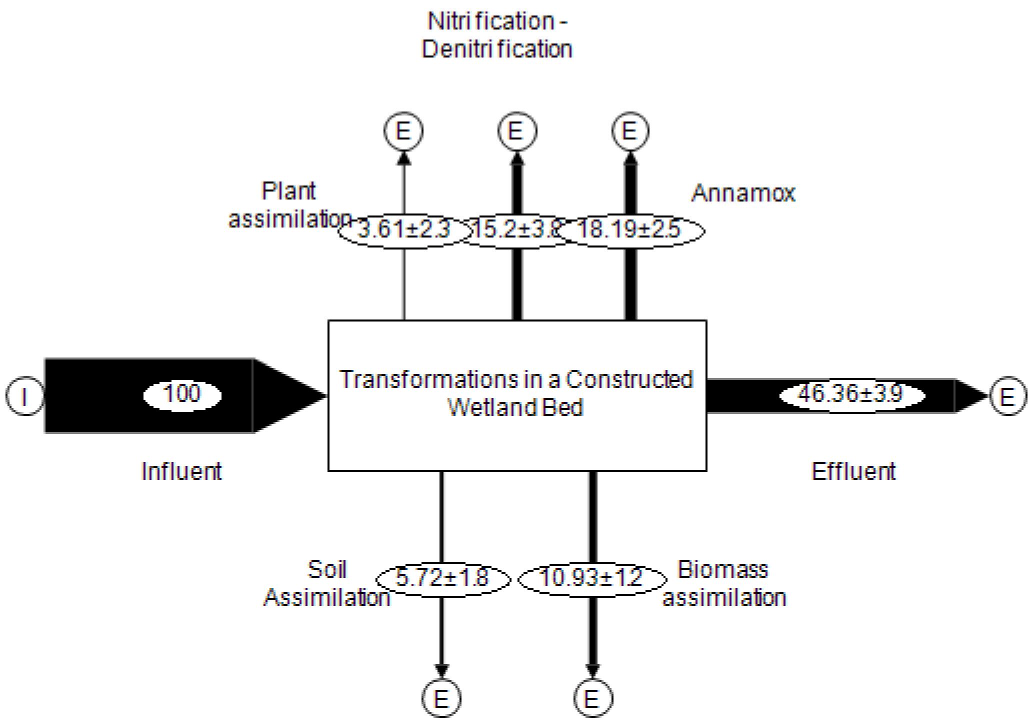


Figure 15: Nitrogen flows in deep bed CW - adapted from Rampuria et al., (2020)

Figure 15 shows the transformations occurring in a deep bed constructed wetland. The average and standard deviation values of pathway removal from two CWs are represented in the flow diagram in Figure 15. Since the nutrient flows are depicted for a deep bed wetland, annamox is observed to be a dominant form of pathway removal, followed by nitrification – denitrification. The plant assimilation is observed to be relatively insignificant as it constitutes a mere 3.6% nitrogen removal. Hence, if plant recovery or reuse for nutrient-rich purpose is a secondary goal in addition to wastewater treatment, alternative configurations of CW can be tried or different plant species having a higher N or P uptake should be chosen. Further, biomass and soil accumulation represent around 11 and 6% removal. It is observed that up to 46% nitrogen remains as residual nitrogen in the treated effluent. Thus, this nitrogen-laden effluent has potential use as reclaimed wastewater for irrigation or landscaping purposes in the vicinity of the treatment plant.

5.4. Performance of nutrient removal in CWs

Several variants of CWs are possible and the choice of plant species, substrate material etc. play a significant role in the nutrient removal. Sand is the most used and readily available materials which also perform well. Gravel is less efficient than sand with respect to nutrient removal. Zeolite is excellent media choice if ammonia and P removal are the priority. Innovative filtrate materials such as limestone, peat, bauxite, shale, dolomite, marble and zeolite along with waste materials such as calcined waste and eggshells are tried in CWs and have been found to have high adsorption rate of P. Table 4 represents the phosphate recovery rates for different substrates in a CW whereas Table 5 represents N removal rates for different plant species (Kamilya et al., 2022).

Table 4: Phosphate recovery rates for different substrates

Substrate	**Recovery**	**Unit**
calcium-containing food waste materials (ex. Eggshells)	23	g P/kg
iron-doped eggshell material	2	mg P/kg
scallop shells	23	mg/g
dolomite	52.91	mg/g
crab shells	108.9	mg/g
iron-rich red soil mixed with sand	1.29–2.22	mg P/g
blast furnace slag	8.89	g P/kg
fly ash	8.81	g P/kg

Table 5: Nitrogen removal rate for different plant species

Species	**Wastewater**	**$g/m^2/year$**
Myriophyllum aquaticum	Swine	120–222
duckweed in CWs	Domestic	195
Typha latifolia	Domestic	100
Pistia stratiotes	Domestic	90
Cyperus papyrus	Domestic	110
Phragmites australis	Domestic	250
Eichhornia crassipes	Domestic	240

6. Pond Systems

This chapter is divided in four sections. The first three sections namely waste stabilization ponds, duckweed ponds and floating wetlands, elaborate on the parameter removal mechanisms in the respective NTS. The last section summarizes the comparison of these systems, especially the algal and duckweed ponds.

6.1. Waste stabilization ponds

The waste stabilization ponds (WSP's) are primarily divided in three categories namely anaerobic, facultative and maturation (or aerobic) ponds. Natural treatment systems such as WSP's have the advantage of better pathogen removal than mechanized systems. Waste stabilization ponds are capable of achieving 4-log removal of pathogens as against the 2-log removal for activated sludge process. Additionally, WSP's are resilient to organic and hydraulic shock loadings due to the long retention time. Waste stabilization ponds was identified as one of the four sustainable methods in the context of developing countries, the other three being CW, UASB and Soil aquifer treatment (Das and Bokshi, 2017).

The aquatic micro and macrophytes in WSP enhance the oxygenation during photosynthesis which affects the interfacial mass oxygen transfer at the air-water interface. Thermal stratification is reported to be prominent for pond depths exceeding 5 m. The underperformance of WSPs has been attributed to increased population growth, unsuitable designs of hydraulic structures, lack of effort in maintaining the ponds and mixing of domestic and industrial sewage (Pishgar et al., 2021).

6.1.1. Algal symbiosis

The interactions taking place between algae and carbonates are depicted in Figure 16 and those are responsible for the fluctuations in pH. pH values above 9 facilitate free ammonia formation that prevent the nitrifying bacterial activity (Rodrigues et al., 2017). DO levels as high as 42 mg/L were reported during daytime owing to the photosynthesis, facilitating aerobic conditions at the pond surface while anoxic conditions at the bottom of the pond (Rodrigues et al., 2017). With reduced light intensity, anoxic conditions turned to anaerobic prominently. The mixed conditions facilitate the growth of denitrifiers majorly as they can survive in all conditions. AOB and annamox bacteria were present in relatively low concentrations (Rodrigues et al., 2017). The nitrifying, denitrifying and annamox bacteria were found to co-exist in the sludge that was deposited at the pond bottom, indicating the presence of multiple pathways contributing to nitrogen removal (Rodrigues et al., 2017).

In WSPs, there is an equilibrium between the production and consumption of oxygen. Hence, there are negligible changes in DO concentrations, and hence carbon dioxide concentrations, which leads to insignificant changes in pH. The pH in WSPs is almost neutral, while the biological processes developing in PPs tend to elevate the pH. This rise in pH initiates nutrient removal in the ponds.

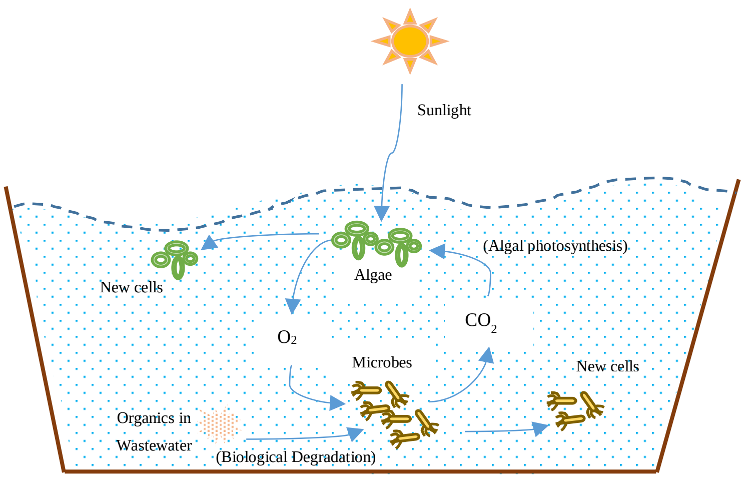


Figure 16: Algal symbiosis occurring in ponds

6.1.2. Removal mechanisms

The complex mechanisms by which nitrogen removal occurs through WSP include adsorption, volatilization, assimilation and chemical precipitation (Mukhtar et al., 2017). The nitrogen removal mechanisms were observed to vary across the depth of WSP.

Organic nitrogen and ammonium are the prominent forms of N in raw sewage. Organic N is usually converted to ammonium through the process of ammonification. Ammonia removal through volatization was not significant as was reported to be around 3% of the applied load in earlier studies (Rodrigues et al., 2017). Although the sediment or sludge deposition reduces the HRT of pond, the sediments facilitate N removal via nitrification, playing a key role in the global N mass balance (Rodrigues et al., 2017). High pH signifies intense algal activity which enhances algal uptake of ammonia (Bastos et al., 2018).

In WSPs, nitrogen is mainly removed by incorporation in the algal biomass, desorption and nitrification- denitrification (Dos Santos and van Haandel, 2021). The negligible mass fraction (5%) of N in algae limits the N removal through algae production. Also, the absence of nitrifying biomass in wastewater effluent prevents the development of nitrification. Hence, desorption of ammonia is a major mechanism and is effective when ammonia concentration becomes considerable at higher pH levels (Dos Santos and van Haandel, 2021). The neutral pH in WSPs facilitate a low rate of desorption.

Nitrogen removal in WSP can occur via algal/microbial uptake and sedimentation or via nitri-denitrification (Linge et al., 2021). The relative importance of each mechanism varies seasonally due to the dependence on phytoplanktonic activity. DOC removal, however, was not found to be varying seasonally. Algal biomass production in maturation ponds significantly removes nutrients. Biodegradation was reported to be the main mechanism for micropollutant removal in both WSPs and oxidation ditches (Linge et al., 2021).

P removal through algal mass is also negligible due to low algae production. Phosphate removal is achieved by increasing pH that can shift the dissociation towards phosphate ion formation (Dos Santos and van Haandel, 2021).

The various pathways for nitrogen removal through a WSP are depicted in Figure 17.

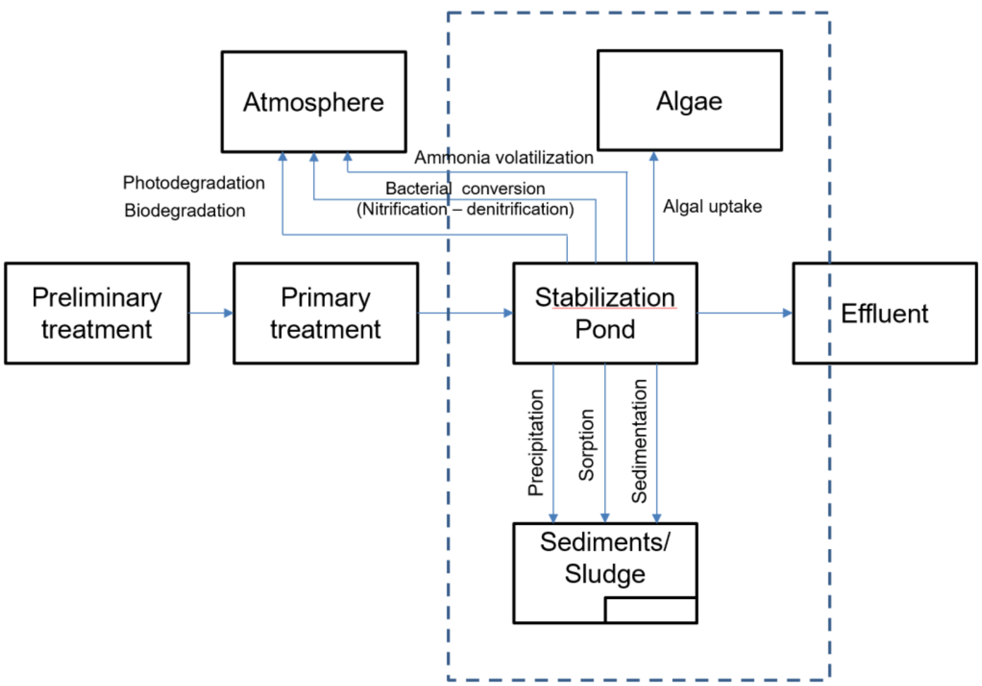


Figure 17: Pathways for nutrient removal in WSP

6.1.3. Polishing ponds

One of the major limitations of WSPs is their inability to remove nutrients while treating wastewater. To overcome this, polishing ponds facilitating efficient nitrogen removal are often provided after anaerobic pretreatment. In case of PPs, colloids are already removed during pretreatment via anaerobic digestion. The photosynthesis in PPs is increased due to transparency, which consumes carbon dioxide thus reducing the acidity and increasing the pH. An elevated pH triggers the N and P removal. The P removal in flow-through ponds is only partial, while a greater removal is achieved in sequential batch of PPs. An empirical model has been developed for P removal which has a logarithmic relation with pH in polishing ponds (Dos Santos and van Haandel, 2021). This model can be used to maintain the pH in ponds to attain the desired phosphate residual concentration. The depth of polishing ponds can be varied to control the efficiency of nutrient removal, as shallow ponds facilitate effective nutrient removal (Dos Santos and van Haandel, 2021).

6.1.4. Performance of nutrient removal in WSPs

The seasonal variations are also prominent in pond systems and the effect of the same is reflected in the performance efficiency as reported by Pinninti et al., (2021) shown in Figure 18.

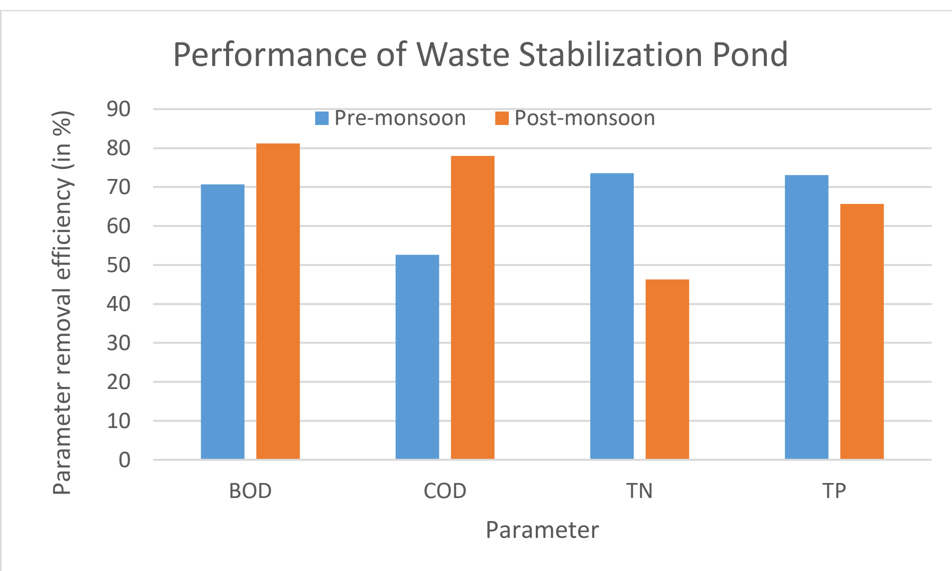


Figure 18: Performance of WSP - adapted from (Pinninti et al., 2021)

6.2. Duckweed ponds

The conventional sewer networks are not cost-effective for small communities, hence the demand and interest in the usage of aquatic macrophytes particularly the duckweeds has grown for treating wastewater at small scales (Erol Nalbur et al., 2004). The introduction of an aquatic plant for example, duckweed, to algal ponds improved the nitrogen removal while reducing algae concentrations. Duckweed species grow rapidly hence achieve a faster coverage on the water surface, creating a unique environment facilitating the adaptation of microbial population. *Spirodela punctata, Lemna minor, Lemna gibba, Lemna obscura, S. punctata, Lemna aequinoctialis, S. polyrrhiza, L. minor* have been identified as the top eight duckweed species (Zhang et al., 2014). Duckweed pond has become popular choice among pond-based systems as it effectively reduces the effluent algal content apart from removing nitrogen and phosphorus.

6.2.1. Characteristics of duckweeds

Duckweeds have a simple structure (as depicted in Figure 19) with a distinguishing characteristic of fronds that are a fusion of stems and leaves as against other vascular plants. They also have short length (103 cm) roots that forms a dense and uniform surface mat (Erol Nalbur et al., 2004). *Lemna aequinoctialis* and *Wolffia microscopica* species are capable of doubling the mass within 20 to 24 hours (Chaiprapat et al., 2003). Moreover, duckweed is capable of thriving and proliferating in swine wastewater due to its preferential uptake of ammonium ions. *Lemna minor* species is known to be tolerant to varying loading conditions due to its high adaptation capacity (Erol Nalbur et al., 2004). Some duckweed species can even tolerate up to 133 mg/L ammonium levels (Chaiprapat et al., 2003). Figure 20 shows photographs of duckweeds as observed in paddy fields.

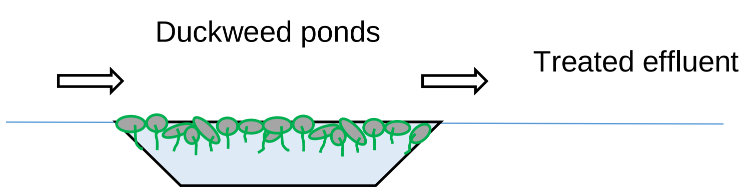


Figure 19: Illustration of duckweed species (fronds) in a duckweed pond

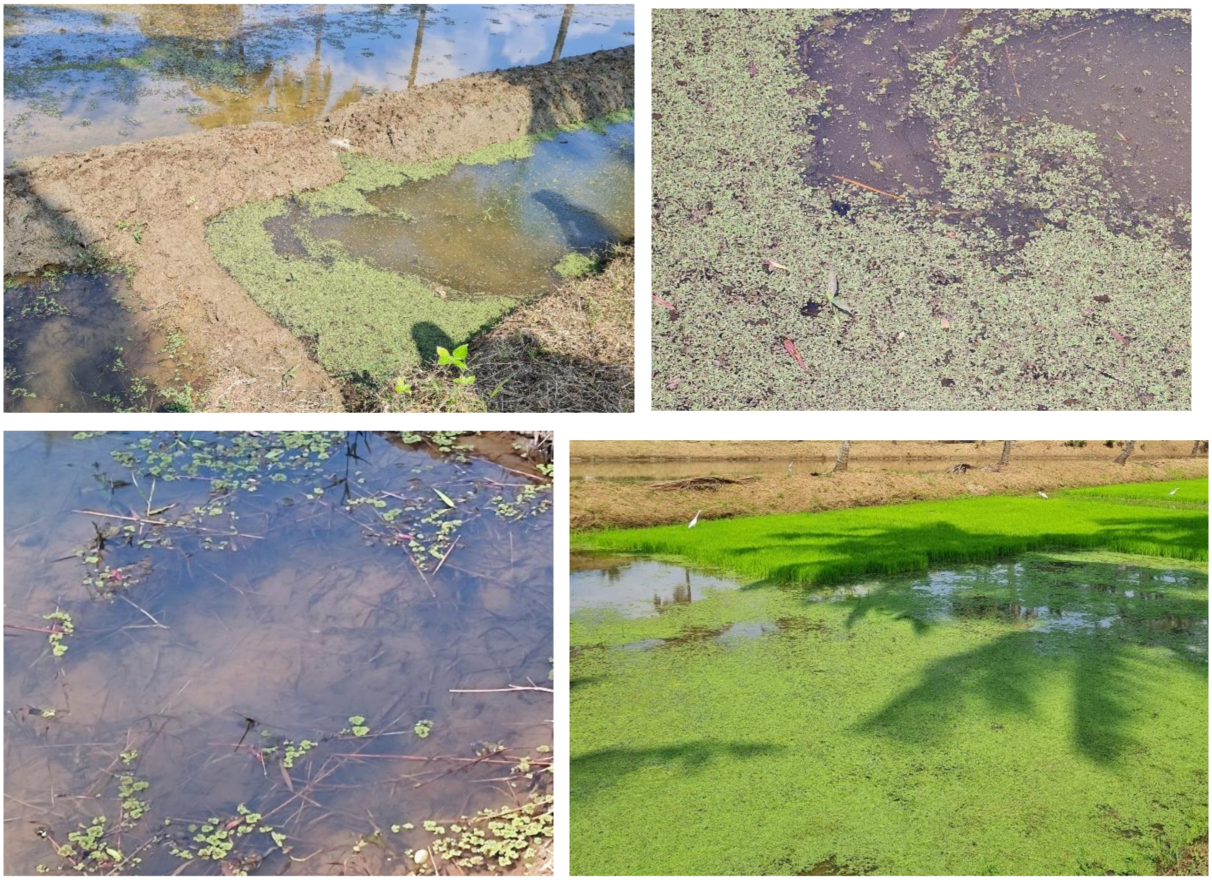


Figure 20: Duckweed species growing in paddy fields

6.2.2. Mechanisms for pollutant removal

Bacterial activity and settling of suspended solids are the main treatment mechanisms in a duckweed pond (Erol Nalbur et al., 2004). Additionally, treatment also occurs by direct assimilation of simple carbohydrates or amino acids. Algae are significant in nitrogen removal as the nutrient is removed via decay and sedimentation, plant uptake, and also the algae provide surface and oxygen for nitrifiers (Zimmo et al., 2003). Parameters such as DO, pH, light intensity and water temperature also affect the nitrogen transformations occurring in duckweed ponds (Peng et al., 2007). Peng et al. (2007) have developed a new model for duckweed pond and have calibrated and further validated the same. This model accounts for 6 forms of nitrogen and 12 transfer processes (as indicated in Figure 21), and can be used to predict the annual transformation and removal of nitrogen. Sediments also impact the nitrogen transformations (Peng et al., 2007); however, sediment considerations increase the complexities of the models and are hence avoided. Denitrification is demonstrated to play a major role in nitrogen removal in pond systems (Zimmo et al., 2004). Although ammonia volatization was earlier considered to be of prime significance in removing nitrogen, several researchers claimed that it accounts for a small fraction while sedimentation and denitrification are the prominent mechanisms of nutrient removal (Zimmo et al., 2004). Zimmo et al. (2004) have also illustrated this as nitrogen removal through ammonia volatization was less than 1.1% in both duckweed and algal-based ponds. Further, plant uptake was also a major mechanism for nitrogen removal.

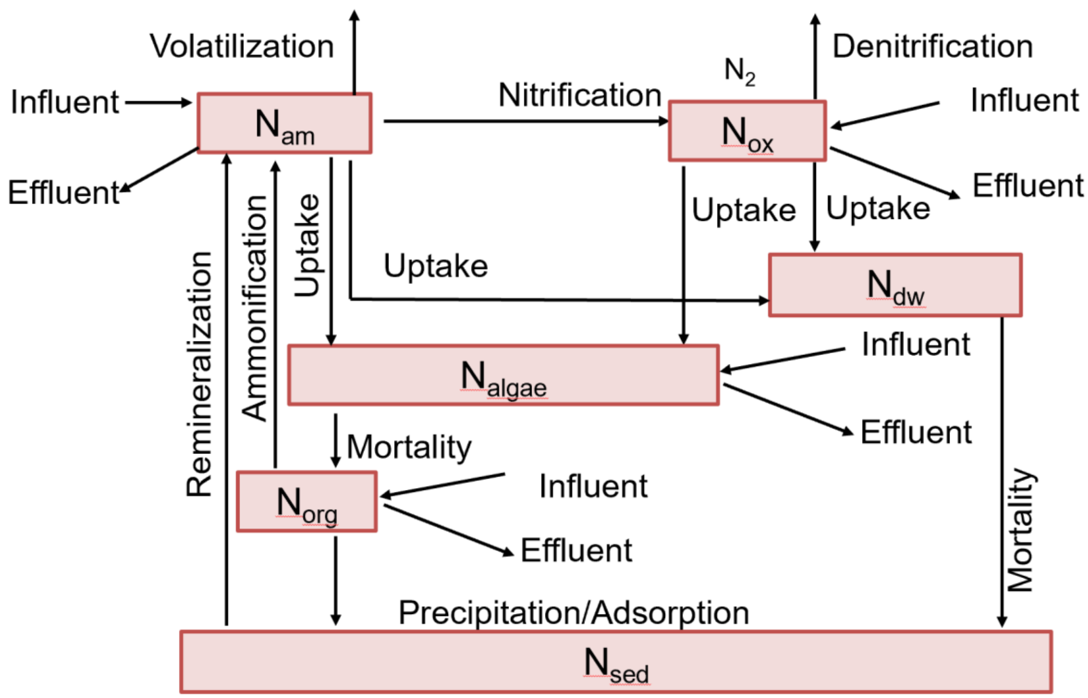


Figure 21: Nitrogen pathways in DWPs - adapted from (Peng et al., 2007)

The various nitrogen removal pathways in a duckweed pond as discussed in literature are tabulated in Table 6 and are described in the subsequent sections.

Table 6: Nutrient removal mechanisms in duckweed ponds as reported in literature

Mechanism	**TN**
Nitrogen assimilation (conversion of inorganic forms to plant biomass)	Sims et al., 2013
Biological conversion (nitrification/denitrification)	Sims et al., 2013
Denitrification	Zimmo et al., 2004
DW ammonium uptake	Chaiprapat et al., 2003
Ammonium transport	Chaiprapat et al., 2004
Duckweed harvesting	Zimmo et al., 2004
Sedimentation	Zimmo et al., 2004 Erol Nalbur et al., 2004

Bacterial activity	Erol Nalbur et al., 2004
Volatization	Erol Nalbur et al., 2005

6.2.2.1. Ammonia volatization

Volatization becomes the significant mechanism in shallow duckweed ponds since the prevailing aerobic conditions do not facilitate denitrification (Erol Nalbur et al., 2004). The ammonia volatization rates in ABPs were reported to be higher than that observed in DWPs (Zimmo et al., 2003). This was attributed to the lower ammonia values in DWPs and the shading effect due to duckweed cover. This shading also prevents heavy diurnal fluctuations in pH. The ammonia volatization is strongly correlated with free ammonia concentration in ponds. At higher pH prevalent in algal based ponds during the daytime, the free ammonia concentrations are higher thus facilitating an enhanced ammonia volatization rate (Zimmo et al., 2003). Also, the volatization rates for ABP and DWPs were found to be equal for equal concentrations of free ammonia hence, the duckweed cover does not remain a physical barrier for nitrogen removal through this mechanism. This might be due to the fact that gas emission from the water occurs through plant stomata ex. methane is emitted from rice fields through plants (Zimmo et al., 2003). Researchers who had claimed ammonia volatization or organic nitrogen sedimentation to be the predominant N removal mechanism had their studies based on theoretical assumptions and not on a complete N balance (Zimmo et al., 2003). The diurnal variation in pH is strongly observed in algal ponds due to photosynthetic activity while the same is absent in duckweed ponds. The volatization rate that was strongly correlated with pH variation over the daytime, decreased in a series of ponds and in winter season (Zimmo et al., 2003).

6.2.2.2. Nitrification – denitrification

Nitrification of ammonia-N occurs in the oxidized root zones of duckweeds whereas denitrification primarily occurs in the sediments or reduced environment of water columns. The DO concentration usually controls the rate of nitrification whereas the carbon sources or nitrification rate govern the denitrification rate (Erol Nalbur et al., 2004). However, there is a series of reactions occurring in the aquatic systems making it difficult to correctly determine the rate controlling reactions. The emission of the powerful greenhouse gas nitrogen oxide occurs during denitrification process and the rate of N_2O in atmosphere is increasing at 0.2 to 0.3% per year (Sims et al., 2013). The methanogens produce CH_4 during the diurnal DO changes in DWPs whereas the nitrification-denitrification emits the harmful N_2O gas (Sims et al., 2013).

Due to the full coverage by duckweeds, the phytoplanktons and submerged aquatic plants that are oxygen providers remain devoid of sunlight (Sims et al., 2013). The DO depletes in the dark and such changes in diurnal DO variation enable a higher nitrogen removal rate than under aerobic conditions (Sims et al., 2013). The duckweed ponds create an ecological niche that limits the nutrients and support the growth of AOA (ammonia oxidizing archaea) (Sims et al., 2013). The low to no levels of DO environment prolifers the growth of anaerobic archaea and methanogens in methane production. Methane and nitrous oxide are the two GHG produced in the duckweed ponds, with methane being the predominant one (>90%) (Sims et al., 2013). Elevated temperatures in the rice paddies have reported increased methane emissions as the soil organic matter decomposes rapidly (Sims et al., 2013).

6.2.2.3. Nitrogen uptake

Nitrogen uptake by duckweeds that was observed to be around 30% during warm periods, however reduced to 10 to 19% during cold periods (Zimmo et al., 2004). In case of regular duckweed harvesting, the nutrient uptake and duckweed growth characteristics govern the nutrient removal (Chaiprapat et al., 2003). Nutrient access by duckweeds depends on the lower epidermis of the leaf and the root. Diffusion is the mechanism by which nutrients are conveyed to the root zone, and should hence be considered in the nutrient recovery aspects of duckweed (Chaiprapat et al., 2003). The study by Chaiprapat et al. (2003) has investigated this diffusion-uptake phenomenon occurring in a static-DWP and developed a mathematical model predicting the ammonium-N recovery in the system.

The advantage of using plant-based systems, especially duckweed, is that they produce tissues that are suitable for human consumption or as animal feed, and are hence promising alternatives from the point of resource recovery (Chaiprapat et al., 2003). The total protein content produced by duckweeds varies from 6.8 to up to 45% and is a function of the dry weight (Chaiprapat et al., 2003). A full-fledged DW cropping system can potentially transform enormous wastewater pollution into an industrial-scale facility of biomass production.

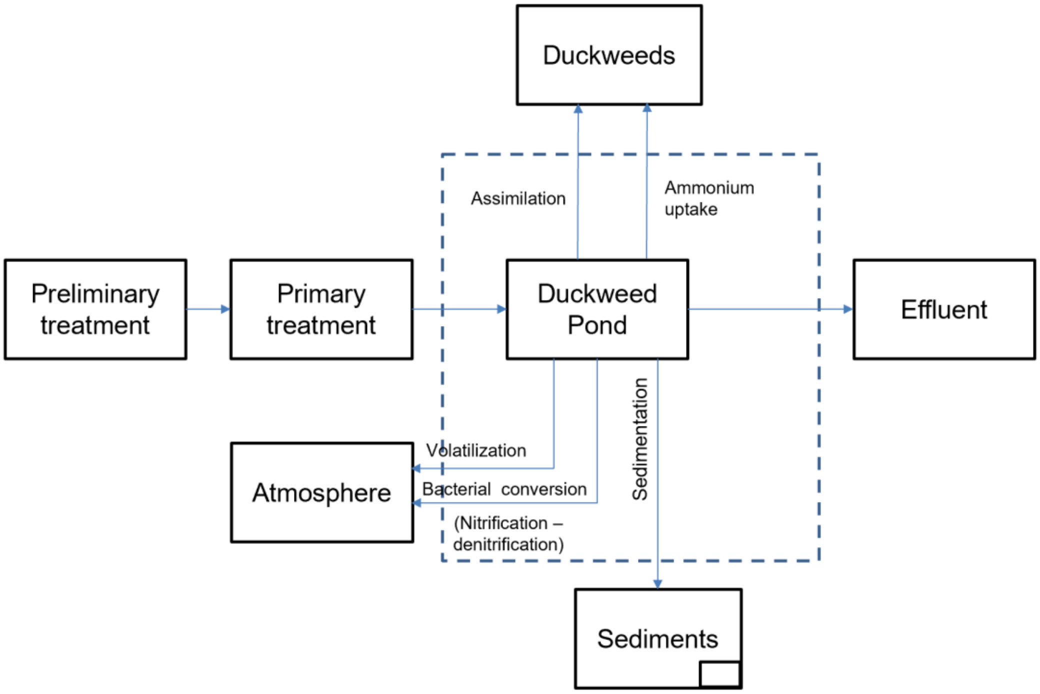


Figure 22: Model for nitrogen transformations in a DWP

Figure 22 shows a typical model for nitrogen transformations taking place in a duckweed pond. The duckweed species uptake nitrogen through either assimilation or ammonium uptake, and the duckweeds can be harvested for the nutrients. Sedimentation i.e. settling of solids under gravity and nitrogenous matter along with it is another pathway for N removal. Further, bacterial activity, volatization. Nitrification-denitrification are other microbial processes taking place in a duckweed pond, which may release nitrogen to the atmosphere.

6.2.3. Nitrogen flows across duckweed pond

Zimmo et al. (2004) have assessed the nitrogen flows and achieved a 91% recovery with respect to nitrogen budget meaning 9% flows were unaccounted. This was attributed to statistical errors in measuring the fluxes, denitrification occurring in biofilms formed on the walls of the pond or duckweed fronds and nitrogen intake by mosquito larva who ultimately left the system (Zimmo et al., 2004).

The nitrogen flows in wastewater based on literature review are depicted in the mass balance in Figure 20. Assuming the influent concentration to be 100%, the nitrogen removal by various pathways is shown as a % removal of influent nitrogen. Average and standard values reported in literature are considered to establish the flow diagram. Seasonal variations are prominent in DWPs and the results in Figure 23 are for performance in a warm season. The unaccounted losses occurring through other pathways are considered as 2% with a standard deviation of 10%. Assimilation % removal along with the standard deviation is calculated in STAN using mass balance.

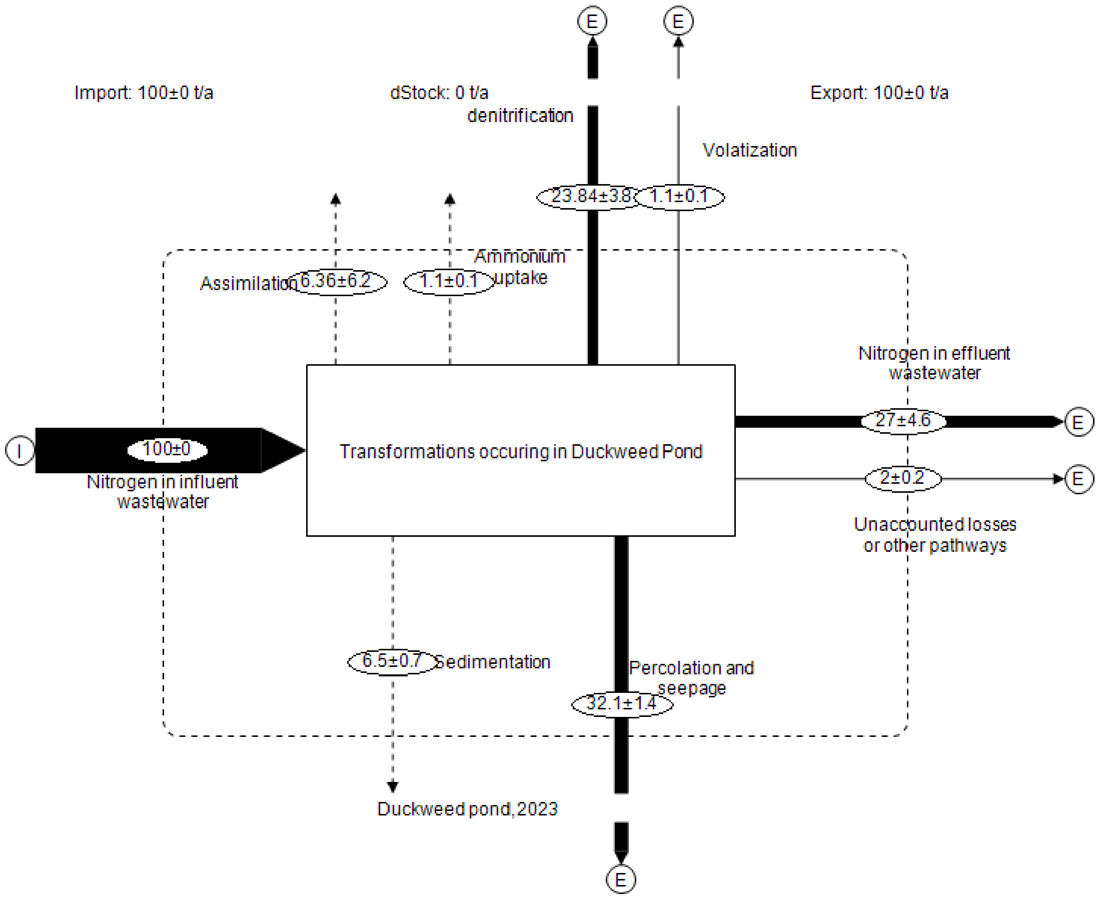


Figure 23: Nutrient removal pathways in DWP

As observed in Figure 23, the prominent pathways for nutrient removal are percolation and seepage into groundwater and denitrification. Plant assimilation or duckweed uptake represents a major pathway however the contribution in terms of N removal is up to 10%. Sedimentation taking place in the pond bed accounts for 6.5%. The prominence of percolation and seepage as nitrogen removal pathway is of significance especially if the groundwater table in the region is high or the pond is hydrologically connected to surface water bodies in the vicinity, since it may possible lead to eutrophication. Approximately 27% nitrogen is present in the treated effluent which can be possibly used for irrigation or landscaping purposes, thereby reducing the dependence on inorganic fertilizers.

6.2.4. Performance of nutrient removal across DWPs

Optimum HLR and mass loading rates for nitrogen removal were reported as 1.2 cm/day and 90 - 160 mg TKN/m^2-day respectively for duckweed ponds investigated for secondary wastewater treatment by Erol Nalbur et al. (2004). The duckweed biomass measured approximately 1236+-3 g of fresh weight/ m^2 (Sims et al., 2013).

The reactors for duckweed ponds showed TN removal rates of 56 to 67% (Erol Nalbur et al., 2004). Considering that a substantial chunk of nitrogen removal occurs at the beginning of tanks, parallel ponds are preferred than a series of ponds in full-scale treatment systems. Or in case of ponds functioning in series, the arrangements can be made for providing influent at different points along the ponds (Erol Nalbur et al., 2004). P and TN concentration higher than 7.9 mg/L and 51.6 mg/L in anoxic pond sewage lead to the death of duckweed fronds (Zhang et al., 2014). Adequate provision of oxygen or oxidant is vital in the efficient removal of N and P. The dead duckweed tend to release P in the sewage thus increasing the TP and phosphate concentrations in the sewage with duckweed (Zhang et al., 2014). Figure 24 represents the performance of DWPs in pre and post monsoon seasons.

Nitrogen removal through ammonia volatization had not exceeded 1.5% of total ammonium N removal (Zimmo et al., 2003). However, in alkaline conditions with pH rising up to 9, ammonia volatization was reported to even account for 21% of the N mass balance. Thus, the role of pH is significant in pond systems.

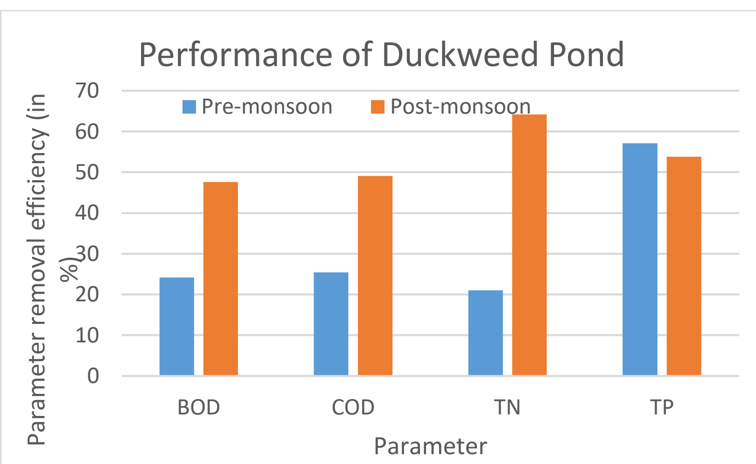


Figure 24: Performance of DWPs – adapted from (Pinninti et al., 2021)

6.3. Floating wetlands

The floating wetlands, which are a variant of constructed wetlands, can actually be regarded as a combination of two natural treatment systems i.e., aquatic ponds along with constructed wetlands. The hydraulic aspects are similar to a detention pond, whereas the rooted plants incorporate the wetland aspects to aid the treatment processes. The stems of plants remain above the water level in the wetland, whereas the roots extend deep in the water column right through the buoyant structure supporting the plants. Floating treatment wetlands comprise emergent wetland species, which are hydroponically grown on structures floating on a pond, as seen in Figure 25. The plants can be considered to grow hydroponically since they obtain the necessary nutrients from the water column which is devoid of soil. The roots hang in the aquatic body and provide a large surface area supporting the growth of biofilm and providing an active area for biochemical processes to take place (Headley and Tanner, 2008). The performance of artificially created floating wetlands has improved the water quality of storm water, combined storm water and sewer overflow, acid mine drainage, sewage, poultry processing wastewater, etc.

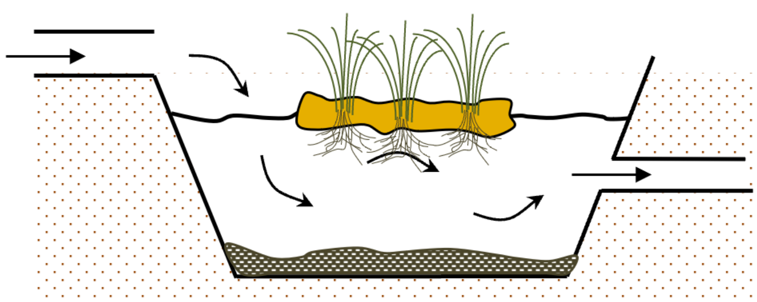


Figure 25: Illustration of a floating wetland

Floating wetlands are a form of in-situ treatment option for the revival of water bodies that are frequent recipients of wastewater. A freely floating mat supporting the growth of plants comprises of mineral sediments, dead organic matter as well as live biomass, which are all held together by roots, rhizomes, and stems. Lentic environments i.e., stagnant fresh water bodies, are suitable habitats for floating wetlands primarily due to the presence of high nutrients and relative stability of water levels. Apart from improving the quality of surface water bodies, floating wetlands also restore the ecological habitat of the aquatic ecosystems and provide an opportunity for revenue generation by harvesting fish or certain crops. Many plants of economic importance are found in the rich speciation of plants found in a floating wetland. As in Kashmir lakes, these floating wetlands are utilized to cultivate vegetables or food crops (John et al., 2009).

The aquatic macrophytes in the water bodies significantly contribute to their productivity. They mobilize the sediment minerals and provide shelter to aquatic organisms like fish and other macro invertebrates. They are known to respond to the changes in water quality and are hence helpful as 'bio-indicators' of pollution. Due to their ability to directly assimilate nutrients, aquatic macrophytes have been used to tackle the eutrophication problem in water bodies (Ramachandra et al., 2017). Unfortunately, the floating wetland agencies are known to sell the product only to improve the aesthetics of the water bodies without considering the engineering aspects of wastewater quality, macrophyte density, and area requirement for wastewater treatment.

6.3.1. Removal mechanisms

The bacteria in a floating wetland system live either in suspended form (in the water body) or as biofilm bacteria (on plant bodies). The N transformations and decomposition in the suspended and biofilm bacteria occur simultaneously. For pH exceeding 6.6, ammonium ions start converting to the volatile ammonia form, the two being nearly equivalent at pH 9.2 while the entire ammonia is present in NH_3 form at pH 12 (Mayo and Hanai, 2017). Both the forms are stable under anaerobic conditions, however, under aerobic conditions, ammonium gets oxidised to nitrate via unstable nitrite ions through nitrification.

Nitrification occurs at a lower rate in DO levels less than 2 mg/L (Mayo and Hanai, 2017). However, the rhizosphere of macrophytes facilitates faster reaction rates due to oxygen release and transport through air voids in roots and stems. Studies report that 90% of oxygen in rhizosphere intensifies the growth of nitrifying bacteria.

Floating treatment wetlands (FTWs) have been reported to effectively reduce the nutrients, metals and suspended solids from the runoff specifically at 18% coverage (Pishgar et al., 2021). The pathways contributing to contaminant removal in floating wetlands include phyto-uptake of nutrients, rhizofiltration i.e. filtration occurring through the root zones and microbial processes that are facilitated by the growth of biofilm on the root surfaces (Pishgar et al., 2021). Permanent removal of nitrogen through systems occurs by denitrification (73.8%), plant uptake after harvest (9.5%), net sedimentation (16.7%) and volatilization (Mayo and Hanai, 2017). Mayo and Hanai, (2017) have assessed the nitrogen transformation and permanent N removal mechanisms in a water hyacinth wetland and also established the significant role of biofilm in a floating wetland, the absence of which would decrease the N removal by 29.4%. The introduction of plants facilitates a higher denitrification than nitrification. However, there is no consensus on the studies regarding contribution of vegetation in nutrient uptake (Mayo and Hanai, 2017). Moreover, the effectiveness of the mechanisms nitrification and denitrification is dependent on the redox state of environment, whether oxic (free oxygen >1 mg/L or anoxic (absence of free oxygen and presence of bound oxygen for example nitrate or sulphate).

6.3.2. Site visits

Floating wetlands have increasingly been used in water body rejuvenation projects in Bangalore, Delhi etc. Delhi Jal Board has also undertaken projects under the City of Lakes project whereby the treated wastewater from STPs (up to secondary treatment units) is further disposed in artificially created lakes. These lakes have aerators and floating wetlands to completely remove the residual BOD and ammonia from the effluent. The in-situ treatment with *Canna Indica* facilitates BOD removal since the plants utilize the organic matter as feed. The spread of roots in floating wetlands is vast and not constrained, unlike the case of constructed wetlands. The sizing of floating wetlands is not defined as a standard; however, 1*1 m rafter is used with 3 to 4 plantations/ sq. m. 6 rafters (2*3 m) comprise one floating wetland bed in the Sanoth Wetland Park, as seen in Figure 26. Casing is used for the plants and a geotextile cloth is used at the top and bottom of the pipe, to facilitate the uniform spread of bio-culture to the plant roots. Also, there is thermocol used as a thermal insulation between the rafters. The meshy roots are known to remove the contaminants through processes of biofiltration, bioconversion and bioaccumulation of pollutants.

Figure 26: Floating wetlands in Sanoth Wetland Park

6.4. Summary

The WSP are commonly known as algal ponds due to the prominent activity of algae. The mechanisms of Algal-Based Ponds (ABPs) and duckweed ponds are almost similar; however, the contribution of pathways differ due to pH differences or difference in properties of plant species (algae vs duckweed). The algal symbiosis is prominent in ABPs while it is absent in DWPs. Some studies have compared the relative performance of both ABPs and DWPs.

The water loss as measured in DWPs was approximately 2% lower than in algal ponds, which was attributed to the shielding provided by the duckweed mat formed on the surface of the pond (Zimmo et al., 2004). The sedimentation flux in ABPs was dominant in nitrogen removal and was even higher than that of DWPs (Zimmo et al., 2004). Elevated temperatures facilitated more algal growth and their decay hence resulting in around 15% increase in the nitrogen accumulated in the sediments (Zimmo et al., 2004). Similarly, in case of duckweed ponds, reduced duckweed cover facilitated increased algal growth leading to a higher nitrogen accumulation in the sediment. Lower N-uptake by the duckweeds during high organic loadings was attributed to the slime layer development on the duckweed roots that prevented nutrient uptake (Zimmo et al., 2004). The duckweed cover also lowers the pH values, thereby affecting ammonia volatization (Zimmo et al., 2004). The water hyacinths have an extensive system of roots having high content of fiber. This makes the harvesting process tedious (Chaiprapat et al., 2003). However, duckweeds have fronds (leaf-like structures) and have low concentration of cellulose and lignin, facilitating easy harvesting. The organic BOD and TSS removal in DWPs was higher as compared to ABPs (Zhang et al., 2014).

7. Case study - East Kolkata Wetlands

The East Kolkata Wetlands (EKW) are a unique feature serving numerous ecological functions and acting as free sewage treatment plants for the city of Kolkata for decades. The sewage of Kolkata city is conveyed to the EKW by the sewer network built by the Kolkata Municipal Corporation. The wastewater is let out from the sewer to open channels, after which it passes through waste stabilization ponds. It is in the stabilization ponds where up to 80% carbonaceous BOD is removed and up to 4-log coliform removal is achieved. Then it is followed by fish ponds where the effluent gets polished and is used by the farmers for irrigating crops. With an area as large as 3500 ha divided into 300 fish ponds, this is the largest site of sewage-fed aquaculture in the world (Asolekar et al., 2014). This system is capable of removing 237 kg-BOD/ day, and it provides a source of livelihood to 74% of the population residing in the adjoining areas (Bhattacharya et al., 2012).

7.1. EKW infrastructure

Kolkata Metropolitan Region Development Authority has 41 ULB's, mostly spread as 42 Ganga river towns. The peri-urban fringes of Kolkata are rapidly developing. Around 1400 MLD sewage is generated in the metropolitan city of Kolkata. Sewage travels around 30 to 35 km from point of generation to EKW till river Matla. There are 3 channels entering in the EKW – Storm Weather Flow (SWF); Dry Weather Flow (DWF) and Fishery Feeding Channel (FFC) (as seen in Figure 27). During the monsoon season, based on flow measurements, excess water is diverted in the SWF which directly goes in the river. The flow is bypassed through the WSP in monsoon and the dilution caters to the treatment of sewage. Lock gates constructed during British period also exist, but those are not used anymore. Also, earlier sedimentation tanks existed near to these gates, that area is currently covered with weeds and plants. There are 9 water quality monitoring stations by Pollution Control Board at strategic locations. Water is ultimately disposed of in the Kulti river.

EKW mainly looks at illegal construction on wetlands, complaints of construction activities or pollution, human threats, settlements, land use changes within EKW etc. As per the 5-year integrated wetland management plan, the budget for EKW is 110 crores (60% Central and 40% State government) out of which the state funds have been approved and community awareness initiatives being carried out using that. Figure 28 illustrates the various stakeholders involved in the operation and management of the EKW along with the specific roles they play.

Figure 27: The storm weather and dry weather channels in EKW

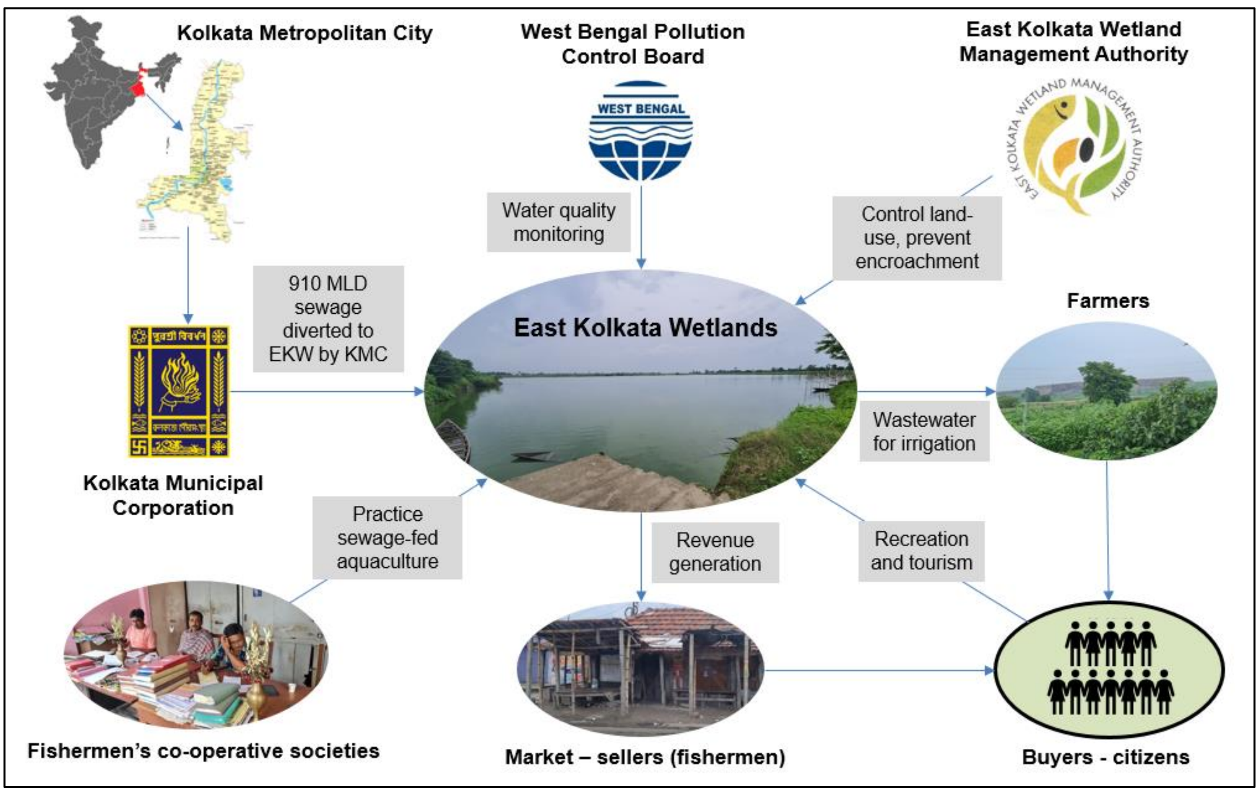


Figure 28: Stakeholders diagram for the EKW ecosystem

7.2. Operation and maintenance

Out of 1400 Million Litres per Day (MLD) sewage generated in Kolkata, 910 MLD (65%) is treated in the wetlands at a nominal cost. There are 13 pumping stations for conveying the sewage from the Kolkata city to the EKW. The EKW are spread over an area of 12500 hectares and comprise of almost 2000 plus water bodies (ponds). Almost 1.5 lakh people residing in the nearby 100 villages are dependent on the EKW for their survival.

The sewage travels a distance of almost 30 km prior to entering the wetlands. During the conveyance itself, microbial degradation and algal symbiosis occurs, thereby treating the sewage partially. The retention time in the EKW is around 30 days. In some ponds, water hyacinth is present generally on 1 m periphery of the ponds so while entering itself nutrient removal occurs then water goes for stabilization. Every water pond has an inlet and outlet. 30% coverage by plant species can be considered ideal. Recently, National Green Tribunal (NGT) persons had also visited EKW site, understood the functional aspects and acknowledged that the wetland systems are functioning adequately. Ideally, entering sewage in Ramsar wetlands is not permitted; but East Kolkata wetlands has special status and is unique in this regard. Despite being Ramsar designated, sewage treatment is taking place in these ecosystems.

Gravity-based sewage conveyance system exists in the EKW, except for low flow conditions when pumps are needed to push the sewage further. The EKW comprise of 4-5 ft deep ponds. Dredging activities are carried out in dry flow (winter period) and calculations are made for how much dredging is to be carried out. Chuna (limestone) is added in case of polluted water. The water bodies are prepared before the onset of monsoon and water is again let in after dredging during late April. The dredging activities i.e. drying up of ponds are conducted in a phase wise manner.

Presently, desilting of the ponds is in progress and 50 out of 260 ponds were desilted at the time of my visit. Almost 15 to 20 ponds are desilted every year.

7.3. Recovery aspects

Considering the variety of goods (such as fish, vegetables), and services (flood protection, biodiversity, carbon sequestration, employment) provided by these natural ecosystems, the East Kolkata wetlands in 2002 have been designated as wetlands having international importance by the Ramsar Wetland Convention.

Nalban bheri and Goltala bheri are huge bheris that are under the Fisheries department. Rest of the water bodies (almost 95%) are privately owned by the fishermen. Bantala bazar is the place where fish are sold on an auction basis (refer Figure 30). The selling price of the fish is a function of the size of fish and it changes daily due to auction method. FFC's serve as inlets to the bheris. There are 144 fishermen's cooperative societies existing in this area since over 50 years. There is no technical know-how, however, natural knowledge is passed on from generations to the fishermen. There is a fish nursery at Chaurchuriya bheri where small fish brought from outside (refer Figure 29). They are provided with locally made fish food (mohua cakes/ mustered cakes) till fish grow to a specific size after which they are then let in sewage ponds. Fish do not feed on the sewage directly. Heavy metals in fish are monitored and are found to be within permissible limits till now. The fish species grown include silver carp, bata, rohu, katla, mrigal, palmo, lilanteka, cyprus etc. 250 to 300 kg/day fish production in this bheri having area of 35 hectare; in monsoon the production goes up to 1000 kg/day. 20000 metric tonnes is the annual fish production reported.


Figure 29: Fishing nursery and sewage-fed aquaculture ponds


Figure 30: Fishing nets and fish markets in the vicinity of EKW

8. Significance of nutrient and energy flows

There are several ways in which industrial and domestic sewage or any other waste generated from human activities such as crop and animal residue, human food can be used to recover the nutrients nitrogen and phosphorus. A systematic chain of recovery needs to be planned to keep the resources in the loop for maximum span rather than letting them deposit in the environment, which makes it more difficult to extract. Cui et al., (2021) have represented various ways of generating anthropogenic nutrient inputs from products of human activities, as shown in Figure 31.

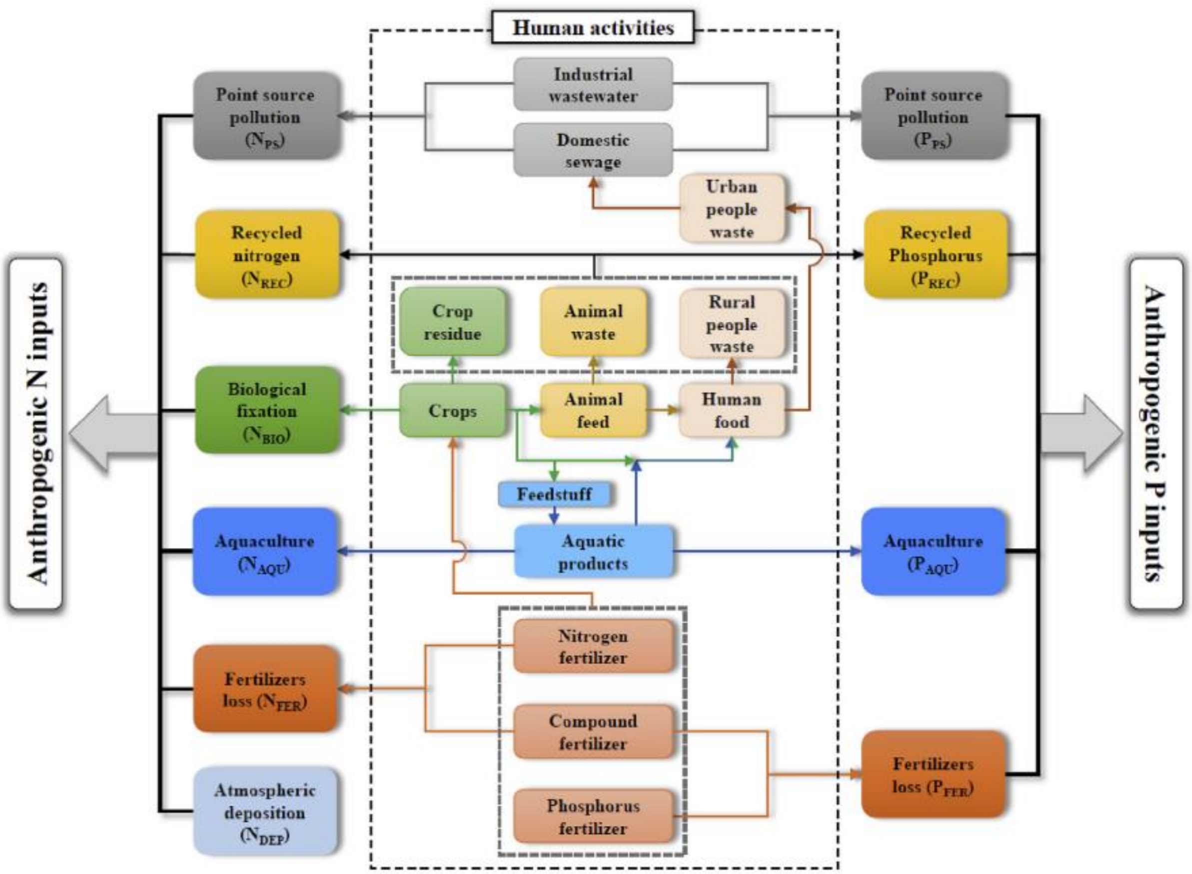


Figure 31: Conceptualization of anthropogenic nutrient inputs from human activities – adopted from Cui et al., (2021)

Further, algae obtained from waste stabilization ponds is also a potential source of resource recovery. Figure 32 depicts generation of bio-fuels from wastewater using microalgae. Several byproducts as well as energy can be generated from algae, from which oil and oil cakes are commonly extracted for the production of biodiesel, bioethanol, biogas etc. Figure 33 depicts the possible recovery options from algae. Thus, if NTS are planned in a holistic manner, several ways of revenue generation, resource extraction and attaining a circular economy can be achieved.

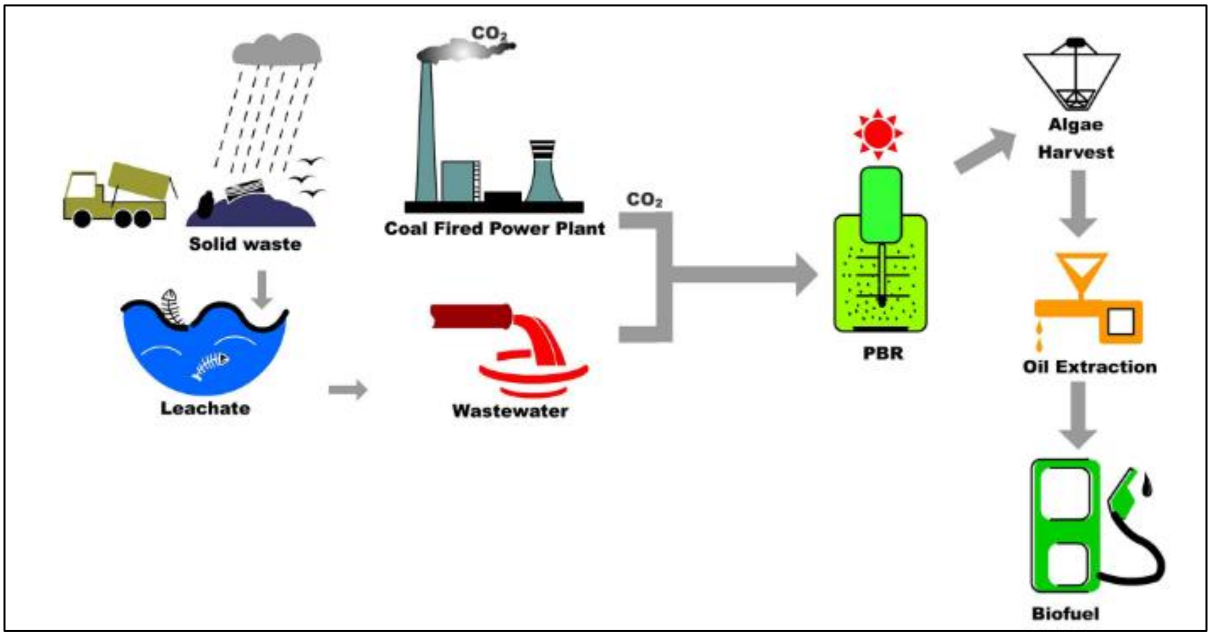


Figure 32: Process chain of biofuel generation - adopted from Witek-Krowiak et al., (2022)

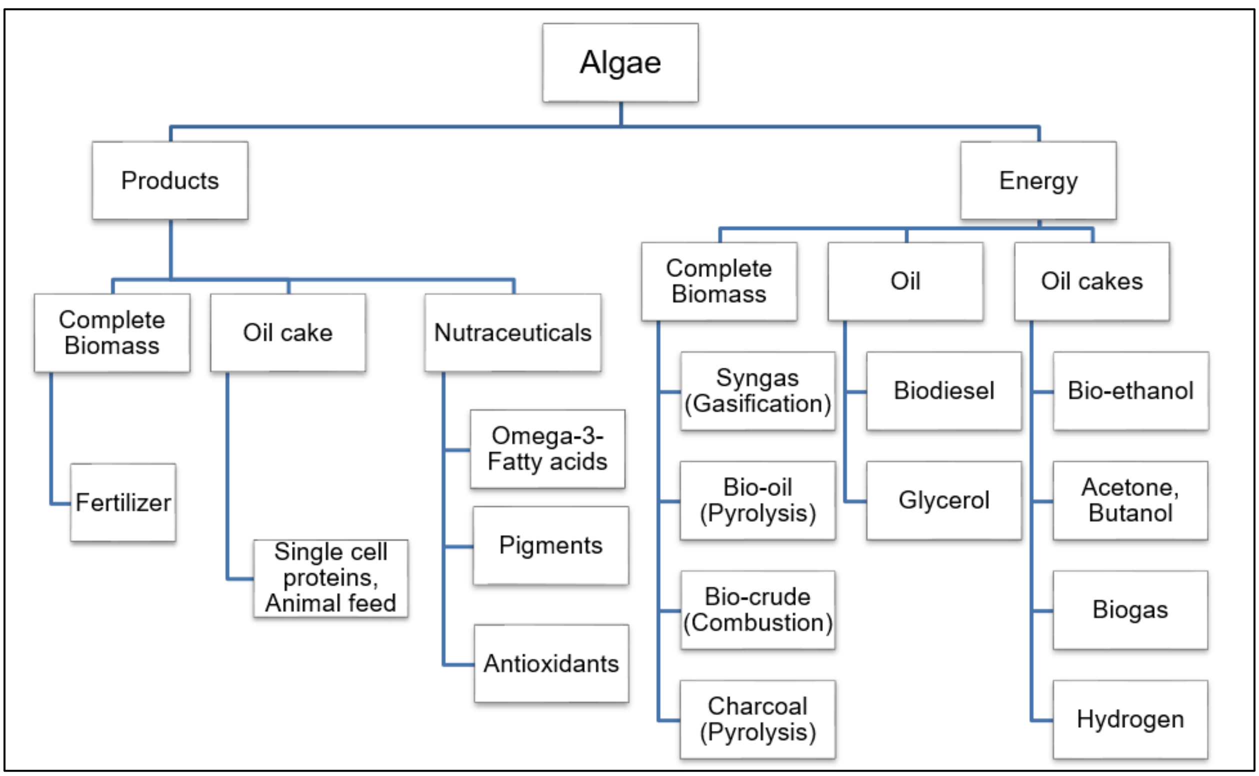


Figure 33: Possible byproducts from algae

Renfrew et al., (2022) have used material flow analysis to assess the market demand of resource vs its recovery potential and accordingly adopted strategies for resource recovery, as illustrated in Figure 34. Thus, material flow analysis can also form the basis of designing resource recovery strategies. Such analysis can be useful in attaining SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production).

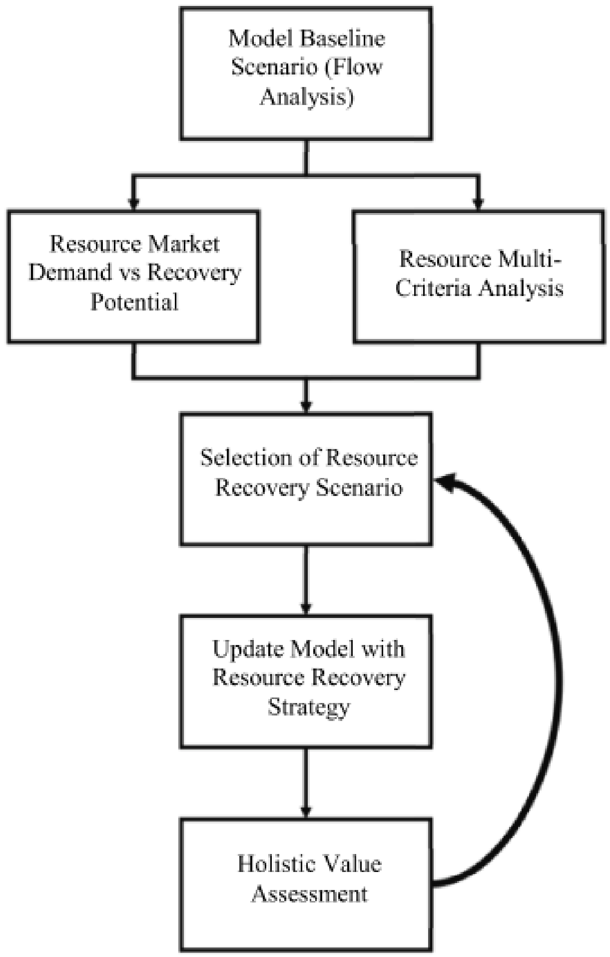


Figure 34: Approach for selecting resource recovery strategies - adopted from Renfrew et al., (2022)

9. Future scope

Cross-sectoral consequences are not considered while developing policies and instruments, which has created an imbalance in demand and supply between sectors (Rasul, 2016). Also, a little effort is made to understand the interdependencies between resource use and policy despite food, energy and water sectors being interconnected. Hence, there is a need for paradigm shift in decision-making framework that recognizes cross-sectoral externalities.

The NTS such as CWs, WSPs and DWPs are potential and low-cost alternatives in developing countries for resource recovery specifically nutrients. NTS can also be used to create a chain of products and bio-based materials. The protein rich duckweed can be used as fish feed or cattle feed. The harvested plants from CWs can be used to produce fertilizers, manure, green composts etc. The algae can also be used for producing ethanol, biodiesel and energy. Moreover, improved quality of effluent ensures the availability of recyclable quality water. Thus, NTS can strategically be used for creating value chain of bio-based materials, water or energy. However, the successful implementation of resource recovery demands the quantification of resources from NTS. Such resource recovery techniques can also facilitate urban agriculture or urban farming. Urban agriculture has intangible benefits such as provision of food locally, reduced transportation distances, reduction in urban heat island effect due to increased green cover, elevated water retention capacity and infiltration rates, larger number of recreation spaces that can also generate employment opportunities.

The nutrient flow analysis presented in this report puts forth a broad understanding of the removal mechanisms taking place in NTS, and the performance of nutrient removal. The mass balance for nutrient has been carried out for CW and DWP. Additionally, the nutrient flows for carbon and phosphorus can also be studied in detail and mass balances for the same can be presented. This will help in comparing the benefits and limitations of NTS in addressing particular treatment goals. Further, the resource recovery technologies extracting nutrients and other by-products from NTS should be explored, resource recovery potential should be quantified and this analysis can be integrated in decision support systems. This will facilitate the transfer of knowledge to urban local bodies or other decision-making and planning authorities who can apply this information and plan the infrastructure for circular economy and resource recovery.

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Disclaimer

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