Review

Constructed wetlands: Perspectives of the oxygen released in the rhizosphere of macrophytes†

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Abstract

Constructed wetland is an economical, efficient and environment friendly technology for the treatment of wastewater. The aquatic plants and microorganisms in constructed wetlands play a key role in the treatment of wastewater. Plants add oxygen during the process of photosynthesis or by direct transport from the atmosphere through their stems and roots to the rhizosphere of constructed wetlands. Moreover, macrophytes provide optimum conditions and surface area for the attachment of microorganisms to perform their activities. The oxygen released in rhizosphere of constructed wetlands has significant impacts on nutrient, gas exchange chemistry and contaminants removal. In this review, we have compiled the published data to explore the mechanism of oxygen release by the roots of macrophytes in constructed wetlands, rhizospheric oxygen measurement techniques, role of climatic factors and ability of different macrophytes in oxygenation of rhizosphere in constructed wetlands. Numerous studies have been carried out on enhancing the efficiency of constructed wetlands by modifying design, macrophyte species and size of wetlands. However, the part of combination of climatic factors, microorganisms and plant species in augmenting oxygen release in the rhizosphere is not explored so far. Therefore, in this review, we tried for the first time to compile all the parameters effecting oxygen released in the rhizosphere of macrophytes in constructed wetlands that are using worldwide for the treatment of wastewater. Moreover, this review article will provide vital information to all researchers who are working on wastewater treatment by using constructed wetlands.

Abbreviations: HF, horizontal flow; **VF**, vertical flow

Keywords: Aquatic plants, Dissolved oxygen, Rhizospheric oxygen, Wastewater treatment, Wetland design

1. Constructed wetlands as alternate wastewater treatment technology

Constructed wetlands are the constructed systems which utilize natural processes for treating wastewater that are using soil, vegetation and microbial communities. They are quite similar to the natural wetlands using natural treatment processes but perform in a controlled environment [1]. Constructed wetlands were first studied in Germany by Käthe Seidel in early 1950s for treating different types of wastewater using wetland plants [2]. In late 1960s, North America used constructed wetlands for the treatment of wastewater by ecological engineering of natural wetlands. Similarly, several pilot scale projects of surface flow constructed wetlands worked for the treatment of municipal wastewater in Australia but this technology did not get much support by the Australian government and public sector, thus the use of wetland technology diminished till 1990s in Australia. The main reason was low phosphorus removal rate and high health risk of public due to mosquito breeding places availability in surface flow constructed wetlands which were the shortcomings of this technology [3, 4]. However, later it was proved that a proper design and management of invertebrates and vegetation can enhance the efficiency of constructed wetlands and minimize the health risk or local population which amplified the usefulness and lessened the downsides of constructed wetlands [5]. In current times, thousands of constructed wetlands are working for the treatment of all kinds of wastewater as they are low cost alternatives in maintenance, operation and construction. Moreover, constructed wetlands can be employed in different combinations of design and components for different types of wastewater and pollutant concentrations [6].

Among the artificially constructed wetlands, horizontal flow (HF), vertical flow (VF) and hybrid constructed wetlands are widely used throughout the world for the efficient treatment of wastewater [1]. In HF wetlands, wastewater is fed in at the inlet and flows slowly through aerobic, anoxic and anaerobic zones in more or less horizontal path until it reaches the outlet zone. The aerobic zone occurs around roots and release oxygen into the substrate. This system is called reed bed and vegetated submerged bed in Europe and the USA, respectively. However, constructed wetlands with VF are fed intermittently with wastewater gradually percolating down through the bed. This kind of feeding provides more oxygen transfer in the rhizosphere and enhances the ability to nitrify. Another innovation in recently developed constructed wetlands is the combined technique approach in which two or more techniques (VF and HF systems) are used for the treatment of different wastewaters. This type of treatment has higher efficiency, less infrastructure requirement and low energy consumption [7]. In addition, the certain length/width ratio of substratum, selection of appropriate plants with long growing time periods, high survival rate, strong resistance, attractive appearance and economic value are other important aspects which are considered in modern designs of constructed wetlands. Moreover, the water and dissolved oxygen infiltration capacity could be enhanced by using suitable sand type and technically arranged infiltration pipes [8].

Constructed wetlands can be successfully employed in developing countries as they are economical and ecologically friendly in pollutant removal of nearly all types of wastewater [9], flood control, provision of habitat for wild life and food production [10, 11]. However, a drawback of constructed wetlands is the decline in their performance to treat wastewater during winter season [12]. Wastewater treatment by constructed wetlands involves chemical, biological and physical processes like precipitation, sedimentation, absorption, adsorption and biological degradation, etc. The processes mainly work under the force of gravity without consumption of energy. However, in certain wetland systems effluent recirculation and supply of artificial aeration can utilize energy which is comparatively lesser to the energy used in conventional treatment systems which makes constructed wetland treatment beneficial and successful in the current times of energy crisis [13]. Although, an extensive research has been done on operation, maintenance and principles related to constructed wetlands, there is a huge gap among different types of constructed wetland systems, macrophytes, and the role of dissolved oxygen released by macrophytes in the wastewater treatment. Therefore, in this review, a combined comprehensive knowledge of constructed wetlands, sources of dissolved oxygen, factors affecting dissolved oxygen, dissolved oxygen measurements techniques and role of dissolved oxygen released by macrophytes in the wastewater treatment is combined for the first time and it will enable the researchers to identify the most efficient and appropriate macrophytes for the treatment of wastewater in constructed wetlands.

2. Role of macrophytes in constructed wetlands

A significant number of plants survive only in aquatic conditions. The larger aquatic plants growing in wetlands are named macrophytes. It is because of presence of macrophytes differentiates wetlands from lagoons. Macrophytes are the essential part of wetland design and possess distinguished properties related to specific wastewater treatment processes like morphological adaptations to grow in water saturated soils, the extensive lacunar systems with constrictions at regular intervals for maintaining structural integrity, high growth rate and ability to incorporate in biomass, etc. [14]. Furthermore, they have specific morphology which can withstand oxygen deficiency [15], presence of air spaces or aerenchyma tissue in their stems, leaves, rhizomes and roots [16] which help them to grow in anaerobic soils [17].

Generally, macrophytes are of three main types i.e. floating macrophytes which have their entire body above the water surface except roots; submerged macrophytes which have their entire body submerged in water, and emergent macrophytes having roots embedded in soil but they are emerged to significant heights above the water (Table 1). Each type of macrophyte has its own potential to perform in different types of constructed wetlands depending upon the morphology of the macrophyte (Table1). The root release of oxygen by floating and submerged vascular plants play vital role in wastewater quality improvement. It is documented that the roots of *Eichhornia crassipes* [18] and *Cymodocea rotandata* [19] do not increase the soil oxygen level substantially but it sustains a thick biofilm of aerobic bacteria by releasing oxygen through the roots which support degradation of organic matter. These plants possess aerenchyma, thick leaves and cuticles, large area of root surfaces and smaller pathways for gas diffusion which support photosynthetically produced oxygen to be transported to the rhizosphere [20-22]. Emergent plants have an extensive lacunar system which comprises 60% of the plant tissue helping in substantial oxygen transport to the well-developed buried roots of the plant and rhizosphere. The functions of different parts of macrophytes in constructed wetland treatment systems are summarized in Table 2. Aerial parts of macrophytes help to reduce the phytoplankton growth by reducing light, provide insulation during winter and store nutrients for the growth of macrophytes. Parts of macrophytes submerged in water help to filter large debris, promote the formation of biofilms and release oxygen for the aerobic degradation of contaminants. Roots and rhizomes in the sediment help macrophytes for nutrient uptake and increase degradation and nitrification by oxygen release. The different types of macrophytes have been used worldwide in different types of constructed wetlands. For example, in surface water constructed wetlands which are shallow basin and/or a combination of basins with soils of 20-30 cm depth for plant growth. All types of macrophytes i.e. free floating, submerged and mostly the emergent macrophytes are growing worldwide in surface water constructed wetlands. The most commonly used genera of emergent macrophytes in these wetlands are Typha, Phragmites, Scirpus, Juncus and Eleocharis. These systems are used to remove all types of wastewater having organics, suspended solids and nitrogen with the help of microbial degradation, filtration, settling, nitrification, denitrification and volatilization, etc. [5]. Similarly, in sub-surface HF constructed wetlands rock or gravel based beds are built which are planted with emergent macrophytes. The most commonly used plants in sub-surface HF constructed are *Phragmites australis*, *Typha latifolia*, *T. angustifolia*, *T. domingensis*, *T. orientalis*, *T. glauca*, *Scirpus lacustris*, *S. validus*, *S. californicus* and *S. acutus*. These systems are used for the treatment of industrial, domestic and agricultural wastewater as well as landfill leachate by the processes of aerobic and anaerobic degradation of contaminants by microorganisms, filtration and uptake by the plant roots and adsorption [8, 9]. Moreover, in VF constructed wetlands, water is fed through large batches containing sand and emergent plants of almost all genera of Typha and Phragmites which are a good source of oxygenation to the substratum are planted in these wetlands. The oxygen supply by the plants is not enough for the aerobic degradation in the rhizosphere of VF constructed wetlands and this is the reason why VF constructed wetlands provide conditions for nitrification and not for denitrification [10, 16]. The oxygen release rate by the roots of different macrophytes is compiled in Table 3. Variations in oxygen release among same groups of plants were identified because of the difference in the substratum and the measuring technique used to quantify the release of oxygen by plant roots. Moreover, different types of macrophytes release variable amounts of oxygen in their rhizosphere due to their morphological differences and oxygen transport mechanisms. All three different types of macrophytes play an important role in wastewater treatment in constructed wetlands. However, the role and the importance of emergent macrophytes in all types of constructed wetlands for their ability to release oxygen through their deep rooting systems and well developed aerenchymal system renders them more suitable for all kinds of constructed wetlands.

3. Sources of oxygen released in the rhizosphere by macrophytes

Oxygen in the rhizosphere of macrophytes play most important role in wastewater treatment and it comes from different sources (Fig. 1). Some scientists proved that the oxygen released by the roots of macrophytes is a byproduct of photosynthesis. A part of the oxygen produced during the process of photosynthesis is transported to the aerenchyma cells (a structural adaptation) of these plants [34-36]. The root release of oxygen in *Potamogeton perfoliatus*, a submerged macrophyte, was measured directly proportional to the rate of photosynthetic oxygen production in plant shoot. Moreover, the oxygen released by the roots was found greater in the growing and smaller plants than the larger plants [27]. However, a significant amount of oxygen is also transported from the atmosphere to the rhizosphere [37, 38]. This type of oxygen transport was observed in yellow water lily *Nuphar lutea*. In these plants oxygen entered the youngest emerged leaves due to gas pressure gradient and entered into the petioles and large blades of older leaves. The direct transport of oxygen was also observed in several emergent plants with cylindrical culms and linear leaves e.g. *Phragmites australis* [39-41]. If the amount of O_2 transported from aerial tissue, the aerenchyma cells and root zone go beyond the plant demands, diffusion may occur into the surrounding rhizosphere of the plants [37, 42]. In well-drained soil pore spaces are filled with air having significant amount of oxygen available for the microorganisms, however, in water saturated or flooded soil, these spaces are filled with water which lack oxygen causing anaerobic conditions for microorganisms, where root release of oxygen by the macrophytes play significant role in rhizospheric oxygenation [14].

4. Measurement of oxygen in rhizosphere of macrophytes

Several techniques have been used to measure oxygen released by roots of macrophytes, each technique having some potential disadvantages (Table 4) [43, 44]. A traditional method of measuring oxygen released from the roots of macrophytes is a split-chamber in which the roots were placed in an oxygen-consuming medium which is separated from the overlying water. This technique is used to measure the total oxygen leakage from the whole plant rhizosphere [19, 48]. In this method oxygen is measured in a whole root system whereas exact measurement of oxygen from specific location cannot be ensured.

The insufficiency of exact oxygen measurement from a specific location in the split-chamber method is dealt with using oxygen micro-electrodes which provides a detailed analysis of oxygen released from a single root and is useful in natural environment [34, 35, 45]. Oxygen micro-electrodes are also used to measure radial oxygen release [46, 47]. This technique helped to find out that the oxygen release rate varies from species to species and ranges from 10 to 60 mg oxygen/cm^2 per min. Moreover, older roots release marginal or nearly no oxygen whereas fine lateral roots released significant amount of oxygen [48]. The oxygen release rates by the roots of macrophytes have different patterns due to difference in the root dimensions, number of roots, and permeability of roots [49]. A drawback discovered in the micro-electrode method was its incapability to measure from a selected spot of the root at a given time and thus, this technique requires a series of sensors if simultaneous measurements in changing oxygen concentrations are required to be measured at a selected spot of the root at a given time [50, 51].

One more technique to measure oxygen released from the roots of macrophytes is the planar optode method. In this method, a two-dimensional image of oxygen distribution with high spatial and temporal resolution is obtained from the sediment [52]. This technique has been used to study dynamics of oxygen in benthic zones and is comparatively more accurate and superior in every characteristic, except for the slower response time compared with electrochemical micro-electrodes [53].

Other approaches of determining oxygen in rhizosphere are oxygen depleted solution, titanium citrate buffer and mass balance methods which are of comparatively low-cost and less technical. However, their accuracy level cannot reach those of technology based approaches. The titanium citrate buffer method has been used to measure the radial oxygen leakage calorimetrically through decolorizing the complex upon oxidation. Thus, after the titanium ions get oxidized the oxygen concentration cannot be detected anymore which is a potential drawback of this process. A shortcoming in the oxygen depleted method is that the rate of oxygen released from the roots of macrophytes is recorded higher by this method as compared to the titanium citrate buffer solution and mass balance method [43, 54, 55]. The mass balance method is based on the number of plants per unit of the surface and mass of the roots. Although this is also a less expensive technique of rhizospheric oxygen measurement, it is unsuitable for assessing the oxygen released by the entire root system [43]. Moreover, by the mass balance method the oxygen release rate is calculated slightly higher as compared to the other techniques. This may possibly be because of the anaerobic degradation of partial organic and nitrogen compounds during night, which is considered as aerobic process in the mass balance measurement [56].

5. Mechanism of oxygen transport within the plant body and roots

Transport of oxygen from shoot to the roots takes place in both aquatic and non-aquatic plants. However, in wetland plants due to the presence of aerenchyma cells, the oxygen transport is very effective [59]. Moreover, in water saturated soils where anaerobic conditions prevail, plants are fully dependent upon the oxygen released in their rhizospheres that support root growth of plants [60]. The oxygen transport to the substrate of the constructed wetlands takes place by the oxygen released from the roots and rhizomes of the macrophytes. The movement of oxygen through the plants takes place either by diffusion or by convection [39, 61, 62] and these transport mechanisms are specific to each plant. For instance, in some floating leaved and emergent plants oxygen is transported by the convective flow of bulk air [39, 63, 64]. This convection is produced by the formation of high pressure in plant's leaves and low pressure in oxygen consuming segments of the plant [61]. The formation of low pressure is mainly based on the solubility of the oxygen used for rebuilding of the plant tissues and the carbon dioxide formed in this process. The formation of higher pressure in the leaves causes air to flow throughout the entire plant body. The transport of oxygen within the plant body by the process of convection may be through-flow or non-through-flow. In many emergent macrophytes with cylindrical culms and lined leaves the through-flow convection is dominated. The through-flow convection is a flow in the channel having both ends open. The convection in such condition is originated by the difference in the pressure at both ends [47].

6. Factors affecting oxygen release in rhizosphere of macrophytes

A number of internal and external factors effect oxygen release from the roots of the macrophytes (Fig. 2).

6.1 Internal factors

In certain macrophytes, the oxygen release rate depends on the internal oxygen concentration. Due to the specific composition of hypodermis and cortex of the roots in macrophytes plants, the radial leakage is prevented and thus, more oxygen is pushed towards the apex of the roots. Thus the oxygen release rate is highest near the sub-apex of the roots and decreases as the distance increases from their apex. Moreover, the oxygen released from the fine lateral roots is significant and nearly no oxygen is released from older roots. In the most recent studies, it is shown that using the micro-optode method of oxygen measurement, the actual peak of oxygen concentration is detected in the rhizosphere in the middle of the root and the thickness of these oxidized zones are several times greater in emergent plants than in typical submersed plants. It is also documented that the oxygen concentration is directly proportional to the diameter of the root [41, 46]. Likewise, the oxygen release rate is higher in growing stages of the plants and the oxygen release rate is many times greater in budding, maturation and elongation stages of growth [44].

6.2 External factors

Macrophyte plants in which oxygen transport takes place by the process of flow convection, the difference in the air pressures at both open ends play a vital role. The difference in pressure may be created by temperature, humidity gradient between the internal gas spaces and the outer environment or by the wind speed gradient around the plant. Furthermore, the humidity-induced convection is also dependent on the temperature difference between inner and outer environment of the plant. This process was demonstrated in different macrophytes having well developed aeration systems [39, 47, 63, 65]. Another process involved in the transport of oxygen is the venturi-induced convection such as the wind blowing over the *Phragmites australis* having its culms snapped off from the tops; this originate venture-induced convection. Venturi-induced convection plays a vital role in humid conditions during development of the plant growth and it provides oxygen to the rhizosphere for plant growth [47]. The root release of oxygen by the macrophyte *Spartina anglica* was investigated in light and dark environment along with the presence and absence of atmospheric oxygen. It was discovered that light played a minor role on rhizospheric oxygenation, however, the concentration of atmospheric oxygen played major role. When plants were deprived of atmospheric oxygen the anoxic zones in the rhizosphere were diminished even in the presence of light and these zones completely disappeared in the darkness [66].

The interconnection between environmental factors and photosynthetic responses has been studied by many scientists in different types of macrophytes (Fig. 2). In *Cymodocea rotundata*, it could be shown that in the absence of light oxygen is not taken from the leaf photosynthesis but from the water column which serves as a large oxygen pool [49]. It was demonstrated that in water lettuce under different light intensities and temperatures, the rate of oxygen release from the roots increased until the optimum light intensities and started decreasing at higher light intensities. The maximum oxygen release rate was recorded at 25°C whereas the net oxygen release was insignificant at 35°C for all light intensities because the respiration rate of the plant was much higher than the gross oxygen release rate in the rhizosphere [67].

7. Role of rhizospheric oxygen in wastewater treatment

The oxygen released from the roots of macrophytes play a key role in wastewater treatment in constructed wetlands [68, 69]. The effective oxygen transfer capacity is one of the main parameters that control the performance of the subsurface flow constructed wetland. In subsurface HF constructed wetlands, the oxygen transfer capacity is limited as compared to the VF constructed wetlands. There are several processes in rhizosphere which are dependent on the oxygen released by roots of macrophytes (Fig. 2), presented in the following sections.

7.1 Oxidation of phytotoxins

The oxygen released by the macrophytes in the rhizosphere forms an oxidative film on the surface of the roots which proves to be protective against the damage caused by toxic components present in the rhizosphere [70, 71]. The thickness of this protective film ranges between 1 and 4 mm and depends on the flow of wastewater in the rhizosphere [63]. As the oxygen in the rhizosphere is consumed by biological and chemical processes, it is compensated continuously by the roots. This constant addition of oxygen to the rhizosphere by the roots of macrophytes plays a key role in the wastewater treatment [43].

7.2 Degradation of organic matter

Organic matter is degraded by either aerobic or anaerobic microorganisms. The rhizospheric oxygen plays a key role in degradation of organic matter by the processes of transformation and mineralization carried out by microorganisms. Along with the atmospheric oxygen diffusion, the oxygen released by the roots of macrophytes produced by photosynthesis also play significant role in organic matter degradation processes. The aerobic microorganisms consume oxygen to breakdown organics to CO_2 and water providing energy and biomass for the microorganisms. In constructed wetlands, the aerobic microorganisms predominantly perform near the roots and their nutrition and energy source is from symbiosis whereas anaerobic bacteria breakdown organic matter to produce methane for nutrition and energy. The biofilms located on the root surfaces play dynamic role in organic matter removal pathways. The main types of reactions with organic matter degradation are aerobic, anaerobic and anoxic degradation. However the most efficient process is aerobic degradation in which oxygen serves as the terminal electron acceptor. In an anoxic environment nitrates, sulfates, and carbonates serve as the terminal electron acceptor which are reduced to oxides [72].

7.3 Nitrogen removal

The nitrifying bacteria use oxygen in the root zone of macrophytes to oxidize ammonia to nitrate. At some distance from this root zone, oxygen gets depleted resulting in anoxic zone where denitrifying bacteria perform. The organic matter in this anoxic zone is degraded in the absence of oxygen and nitrates are converted to nitrogen gas which then escapes to the atmosphere. In addition, in anoxic zone, anaerobic processes such as methanogenesis, sulfate reduction, and denitrification take place [72]. The degradation of organic matter in the anaerobic zone is also carried out by the process of fermentation that produces carbon dioxide and methane. This interaction of aerobic, anaerobic and anoxic zones and their respective microorganisms is very important for efficient and complete decomposition of organic matter in constructed wetlands [73].

The major removal mechanism for nitrogen in HF constructed wetlands is denitrification. The removal of ammonia in HF constructed wetlands is inadequate due to lack of oxygen in the substratum due to permanent water saturated conditions [64, 65]. However, in VF constructed wetlands, the settleable organic compounds are removed by deposition and filtration by the beds and soluble organic compounds are degraded aerobically or anaerobically by microbes. As aerobic degradation is much more rapid than anaerobic degradation and because the oxygen transfer capacity is higher in VF constructed wetlands, therefore, nitrification is usually higher in VF constructed wetlands as compared to HF constructed wetlands [76--79].

7.4 Controlling redox potential and immobilization of heavy metals in the rhizosphere

The plants have the ability to change the redox potential of the rhizosphere, enhance the metal uptake and cause immobility of certain metals by releasing oxygen through their roots. Thus, the soils which are vegetated are having higher redox potential as compared to non-vegetated soils. This is because of the oxygen released to the rhizosphere by the roots of plants. This oxygen helps in oxidation of heavy metals like iron *and* manganese which develop root plaque [26] and chemical transformation of metals in the rhizosphere. Moreover, the iron and manganese root plaque increases the adsorption of zinc and other metals with the help of iron/manganese hydroxides. As a result the concentration of metals in the root plaque is increased as compared to the soil. In addition, the reduced soil causes immobility of the metals within the soil [80].

There are several processes in rhizosphere which are dependent on the oxygen released by roots of macrophytes (Fig. 3) including oxidation of phytotoxins, [68], increasing immobilization and chemical transformation of heavy metals [59], supporting microbial activity, controlling redox potential of the rhizospheric environment and enhancing nitrification [81]. The oxygen released by the macrophytes in the rhizosphere forms an oxidative film on the surface of the roots which proves to be protective against the damage caused by the toxic metals in the soil [80, 82].

8. Conclusion

In previous studies regarding constructed wetlands, the emphasis was given mainly on design, technological issues and biological aspects of constructed wetlands. However, this review mainly focuses on constructed wetlands types, macrophytes used in constructed wetlands and the importance of dissolved oxygen release by the roots of macrophytes in wastewater treatment. We concluded that the macrophytes and oxygen released by the roots of macrophytes are the vital components of constructed wetlands because they are the main source of oxygenation in the rhizosphere, which in many cases become the rate limiting factor in wastewater treatment processes. Moreover, dissolved oxygen released by different macrophytes varies mainly due to three reasons, (i) different dissolved oxygen measurement techniques, (ii) different mechanisms of oxygen transport into rhizosphere by the roots of different macrophytes, (iii) different environmental factors. So far, only few macrophytes (mainly Typha, Phragmites, Scirpus, Juncus) have been tested for wastewater treatments in constructed wetlands. Many other macrophytes such as *Centella asiatica*, *Nelumbo nucifera*, *Nasturtium officinale*, *Ipomoea aquatic*, etc., remained unexplored so far. In addition, a specific guideline for the construction, design, maintenance, economic and environmental impact of constructed wetlands must include recommendation about type of vegetation, rate of oxygen released in the rhizosphere and the relevant and suitable oxygen measuring technique along with the climatic conditions of the study area. Keeping in mind the importance of rhizospheric oxygen in treatment processes, further research on the influence of combination of different environmental factors on macrophytes can prove to be crucial in enhancing constructed wetland efficiency. Moreover, for each country and community the management strategies, environmental consequences and cost of the constructed wetland technology installation should be clearly defined. Thus, broad research on the investigation and enhancement of the oxygen released in the rhizosphere by macrophytes can prove a step forward to the “alternate wastewater treatment technology”.

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Figure 1. Schematic diagram showing the different sources of oxygen in the rhizosphere of macrophytes.

Figure 2. Different factors affecting oxygen released by the roots of macrophytes in the rhizosphere.

Figure 3. Role of oxygen released in the rhizosphere of macrophytes

Table 1. Types of macrophytes used in constructed wetlands.

Type of macrophytes	Morphology	Type of constructed wetlands
Emergent macrophytes	Extensive internal lacunar system, well developed roots buried in the soil, shoot emerged from the water surface	Free surface HF Subsurface HF Subsurface VF
Floating macrophytes	Well-developed rhizome system, Buoyant leaf bases floating on water surface	Free surface HF
Submerged macrophytes	Aerenchyma, small gas pathways, thick leaves and cuticles, entire plant body submerged in water	Free surface HF

Table 2. Functions of macrophytes in constructed wetland treatment systems.

Macrophyte plant body	Role in wetland treatment process
Aerial part	Reduce phytoplankton growth by reducing light Provide insulation during winter Reduced resuspension by reducing wind speed Aesthetic pleasing appearance of system Storage of nutrients
Part submerged in water	Filter out large debris Help in better sedimentation and reduce resuspension Promotes the formation of biofilms of microorganisms by providing surface area Increased aerobic degradation by oxygen release
Roots and rhizomes in the sediment	Uptake of nutrients Reduce erosion Prevent clogging in VF systems Increase degradation and nitrification by oxygen release Release antibiotics

Table 3. Oxygen release rate by the roots of macrophytes

Macrophyte and media	Root oxygen release	Reference
Phragmites australis (soil)	0.02 g/m^2 per day	[23]
Phragmites australis (hydroponic)	5-12 g/m^2 per day	[23]
Phragmites australis (gravel)	0.8 g/m^2 per day	[24]
Phragmites australis (sand, gravel)	4.1 g/m^2 per day	[25]
Typha latifolia	0.8 g/m^2 per day	[24]
Pistia stratiotes	0.25--9.6 g/m^2 per day	[26]
Potamogeton perfoliatus	0.5--5.02 g/m^2 per day	[27]
Scirpus validus (gravel)	28.6 g/m^2 per day	[28]
Scirpus validus (gravel)	7.2 g/m^2 per day	[29]
Scirpus validus (gravel)	0.8 g/m^2 per day	[30]
Scirpus validus (plastic media)	0--10.3 g/m^2 per day	[28]
Scirpus validus	5--45 g/m^2 per day	[31]
Acorus calamus (linn, scoria)	38.4 g/m^2 per day	[32]
Juncus effuses (titanium citrate solution)	$9{\cdot}5 \times 10^{-7}$ mol O_2/h per root	[33]
Juncus inflexus (titanium citrate solution)	$4{\cdot}5 \times 10^{-7}$ mol O_2/h per root	[33]
Juncus ingens (titanium citrate solution)	126 mol O_2/h per root	[33]
Glyceria maxima (soil)	2.3×10^{-8} g/cm^2 per min	[23]
Irus pseudocorus (soil)	2×10^{-8} g/cm^2 per min	[23]

Table 4. Advantages and disadvantages of oxygen measuring techniques in the rhizoshere of macrophytes.

Method	Advantage	Disadvantage	Reference
Split-chamber	Measures whole plant rhizosphere oxygen release	Does not measure from a specific point	[20, 45]
Micro-electrode	Measures of single root oxygen release; radial oxygen loss; in natural environment	Measures from a selected spot; series of sensors is required	[34, 35, 44, 46]
Planar optode	Stable, measures accurately, sensitive under low concentration	Responds slowly, latest techniques needs further development	[57, 58]
Oxygen depleted solution	Less expensive; no complicated technology involved	Less accurate; measures slightly greater concentration of oxygen; consumes oxygen from within the system	[42]
Titanium citrate buffer	Less expensive; no complicated technology involved	Less accurate; Measures slightly greater concentration of oxygen release; does not detect oxygen after a certain step	[53, 54]
Mass balance	Comparatively less expensive	Unsuitable for measuring oxygen released from the whole root system	[42, 55]

Figure 1

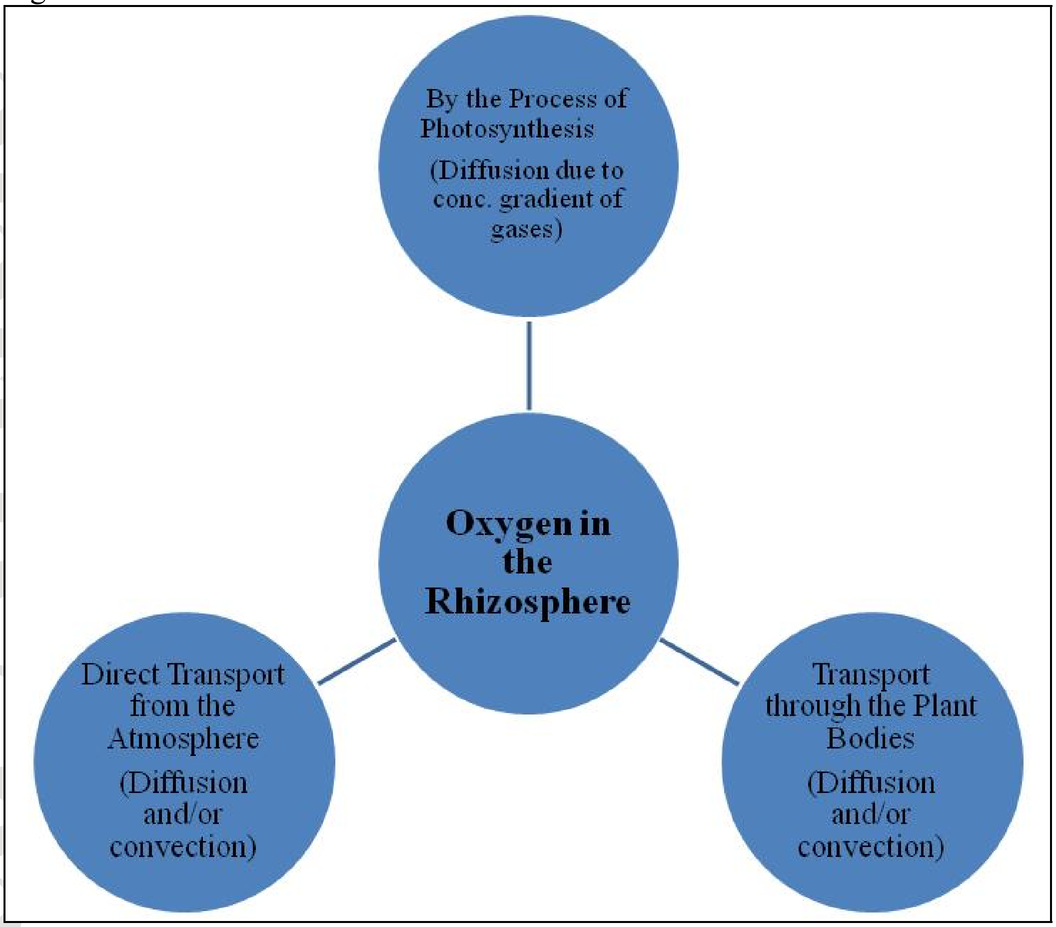

By the Process of Photosynthesis
(Diffusion due to conc. gradient of gases)
Oxygen in the Rhizosphere
Direct Transport from the Atmosphere
(Diffusion and/or convection)
Transport through the Plant Bodies
(Diffusion and/or convection)

Figure 2

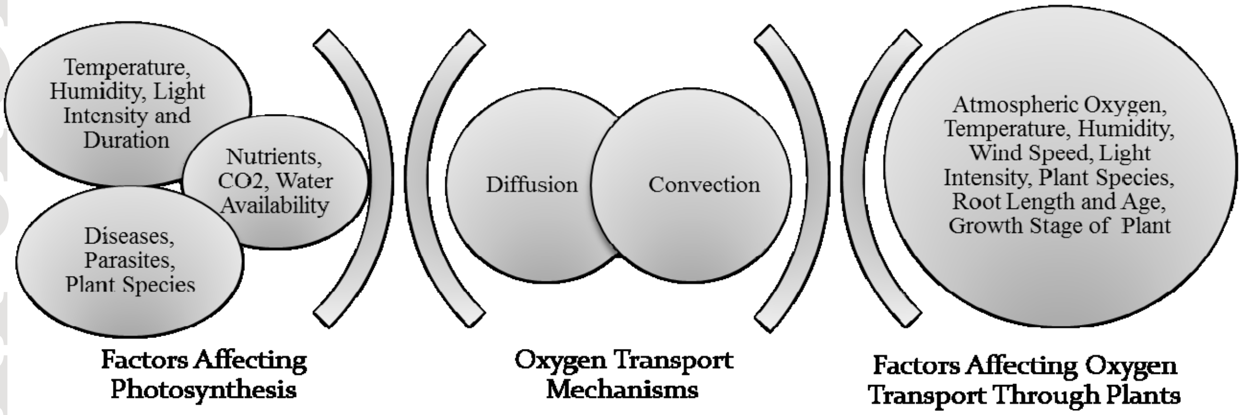
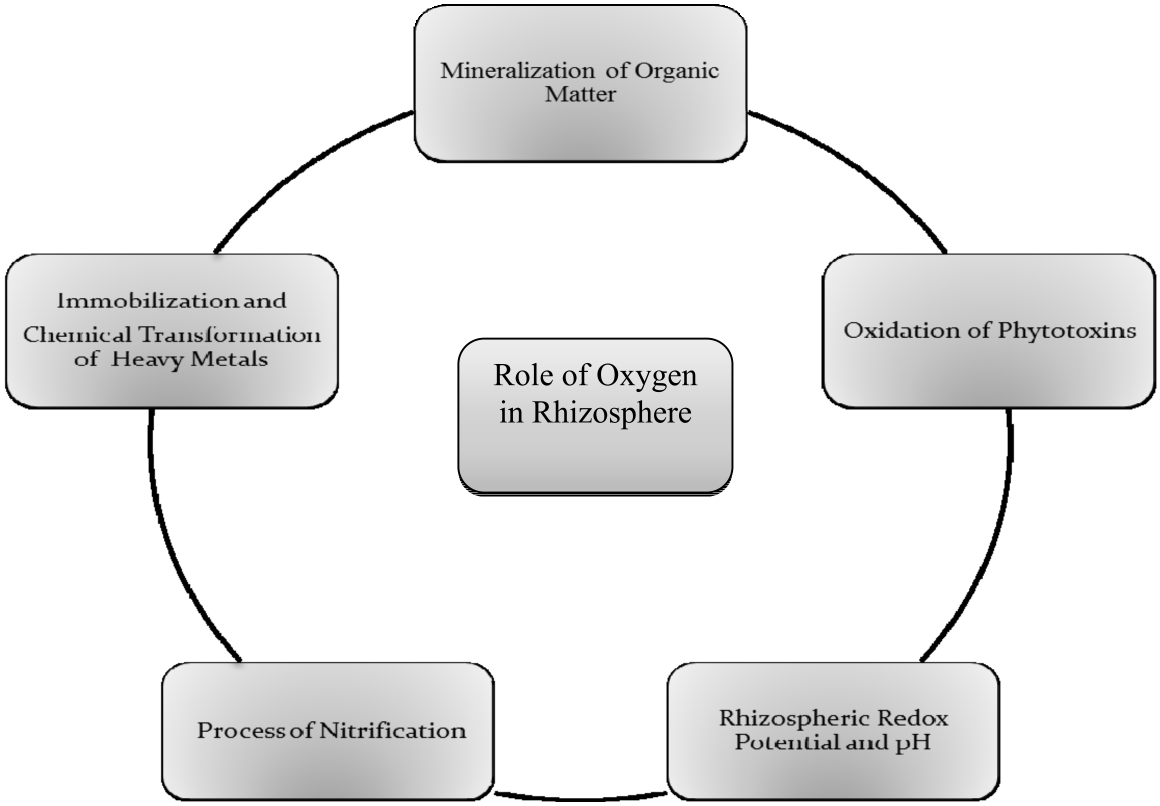

Temperature, Humidity, Light Intensity and Duration
Nutrients, CO2, Water Availability
Diseases, Parasites, Plant Species
Diffusion
Convection
Atmospheric Oxygen, Temperature, Humidity, Wind Speed, Light Intensity, Plant Species, Root Length and Age, Growth Stage of Plant
Factors Affecting Photosynthesis
Oxygen Transport Mechanisms
Factors Affecting Oxygen Transport Through Plants

Figure 3


Mineralization of Organic Matter
Immobilization and Chemical Transformation of Heavy Metals
Role of Oxygen in Rhizosphere
Oxidation of Phytotoxins
Process of Nitrification
Rhizospheric Redox Potential and pH