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TOWARDS RECOMMENDATIONS FOR DESIGN OF WETLANDS FOR POST-TERTIARY TREATMENT OF WASTE WATER IN THE BALTIC SEA REGION – GDAŃSK CASE STUDY

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Abstract

There are many challenges that need to be addressed if the far reaching objectives on high environmental status as required in the EU Water Framework Directive and the Marine Strategy Framework Directive will be met in the Baltic Sea Region within the next decade. For wastewater treatment plants (WWTP) this implies, in spite of the many improvements made during the last decade, development and introduction of new technology to further reduce eutrophying compounds, hazardous chemicals and pharmaceuticals. Constructed wetlands when properly designed and operated have been shown to be robust systems with low energy requirements that may not only reduce many types of pollutants but may also provide many additional ecosystem services beyond requirements generally imposed by authorities. For example, they may support and enhance biodiversity and be used to convert brownfield areas in urban landscapes to recreational areas. Reduced cost is possible if treated water is reused in industry or for irrigation. In a project, supported by the Swedish Institute, a group of scientists, a water company and water using industry has together with local authorities through workshops, field studies and literature studies worked on finding a general first recommendation on design and operation. In this paper we will present the scientific rational and legal constraints for the general design and operation of a wetland system for post-tertiary treatment of waste water from WWTPs using Gdańsk as an example. The proposal includes a first part, which mainly will be focusing on pollutant and pathogen removal using particle traps and a HSSF wetland on land owned by the WWTP and a second part consisting of a FWS wetland which, in addition to further polishing the water, will enhance biodiversity and provide recreational areas on derelict land owned by the city.

Keywords: discharge limits, ecosystem services, sustainable cities, treatment wetlands, waste water

1 INTRODUCTION

Many challenges need to be addressed if the far reaching objectives on high environmental status as required in the EU Water Framework Directive and the Marine Strategy Framework Directive will be met in the Baltic Sea Region within the next decade. For wastewater treatment plants (WWTPs) this implies, in spite of the many improvements made during the last decade, development and introduction of new technology to further reduce the discharges of eutrophying pollutants and hazardous chemicals including pharmaceuticals. Since the EU in 2010 imposed a limit on total nitrogen concentration to 10 mg/l for effluents from WTTP with more than 100.000 personal equivalents (P.E.), local authorities and WWTP operators are trying to improve the treatment processes towards minimizing the discharge of nitrogen to the recipient. The most frequent way to meet this requirement is to improve the treatment processes by introducing high-tech and expensive solutions e.g. enhance biological nutrients removal using technology such as University of Cape Town (UCT) or the A^2O. An alternative solution could be the application of treatment wetlands (TWs) which are designed to take advantage of the same processes that occur in natural wetlands. Wastewater treatment systems based on TW technology are nowadays commonly used not only for treatment of municipal wastewater, but also for storm water treatment systems as well as industrial wastewater treatment e.g. landfill leachate or reject waters [1-6].

Using physical, chemical and biological processes occurring in natural wetland ecosystems – but in a controlled environment created in TWs – high rate removal processes of organic matter (including hardly degradable organic matter such as PAHs and pesticides) and nitrogen compounds can be achieved. These processes are dynamically taking place next to each other, therefore influencing the main process of wastewater treatment. Wastewater treatment in TWs is a result of the interaction between plants, soil and microorganisms [4-6]. The two existing databases on TWs [7,8] are showing that several hundred TWs are polishing secondary or tertiary wastewaters all over the world and in Sweden TWs were constructed during the end of the last century to decrease the nitrogen discharge of tertiary treated waste water in conventional WTTPS to the seas thus, they have also been used for post-tertiary treatment in the region. TW design can be divided into 2 broadly defined groups; wetlands with surface flow often termed free surface water wetlands (FWS wetlands) and wetlands with subsurface flow. The wetlands with subsurface flow can be grouped into two types those with horizontal flow (HSSF wetlands) and those with a vertical flow (VF wetlands) the former being more common [6]. The have been used for various purposes and a comparison of performance between the FWS and HSSF for waste water treatment has recently been conducted [9].

TWs used for tertiary treatment showed high removal rates for all the organic residual substances, achieving effluents with less than 5 mg BOD_5 l^{-1} and offering an optimum environment for capturing, by adsorption phenomena, the bioresistant pollutants. In addition, their high filtration capacity results in less than 10 mg TSS l^{-1} in the final effluent and in many cases good nutrient reductions, in particular for nitrogen. In the TW mesocosm, anaerobic conditions often prevail, particularly in HSSF, due to the relatively low re-aeration potential of the units. As a consequence, having an appropriate nitrification in the mechanical section of the wastewater treatment plant (the new nitro-denitro section), the tertiary TW can enhance denitrification process fairly efficiently. TWs have proved to be the more efficient means of nutrient control, despite the season ability of the involved removal processes and within reasonable economic limits, in the comparison with traditional biological/mechanical treatments (nitro-denitro compartments in common activated sludge plants). In reviewing TW technology for wastewater treatment, [10] recently concluded that they can be accepted as a valid "ecotechnology" for reducing the loading of nutrients in the final receiving water body. Moreover, the last experience with renaturalisation of conventional treated effluent in TWs proved the possibility to reuse the effluent from TWs in a nearby industry [11,12]. TWs may also function for the removal of persistent pollutants such as trace elements (i.e. heavy metals) and persistent organic pollutants (POPs) including emergent pollutants such as endocrine disrupters and mutagenic substances [6,13,14]. It has been found that many of the heavy metals are associated with the particulate matter and therefore design options using sediment traps or reactive filter material may result in the concentration of them in a minor section of the wetland avoiding the dispersion of the pollution in the whole wetland [2,15]. TWs when properly situated and designed may also contribute to many additional ecosystem services beyond those requirements generally imposed by the authorities such as enhance biodiversity as has been shown for birds and animals in the rural Swedish landscape [16]. It should also be possible to use them when converting brownfields and derelict land in urban landscapes to recreational areas.

Considering the vast scientific and practical knowledge on TWs in general in the region and the practical experience of post-tertiary treatment of effluents in Sweden we are now initiating a process of knowledge exchange in the region promoting the use of TWs in post-tertiary treatment of waste water. The project has in its initial phase been supported by the Swedish Institute and here we present our general first recommendations of design. The long term goal of this project is to by analysing the state of the art, capacity building and networking to receive funding (national and European) for research on the design, operation and monitoring of treatment wetlands for post-tertiary treatment and reuse which will meet ecological and human demands in urban settings throughout the Baltic Sea Region.

2 MATERIALS AND METHOD

The recommendations presented in this paper are based upon wetland science literature published in open international journals and conference proceedings. In the project 3 workshops were arranged. They consisted of lectures by the scientist participating in the group, lectures by invited experts and study visits. The two first workshops were held in Sweden enabling study visits to the Magle wetland in Hässleholm and the Ekeby wetland in Eskilstuna, both FWS wetlands used for post-tertiary treatment of waste water. The third workshop was held in Gdańsk as representatives from the owners and operators of WTTPs (Gdańska Infrastructura, Wodociągowo-Kanalizacyjna Sp, z.o.o.), authorities (e.g. City of Gdańsk) and a refinery (Grupa Lotos S.A.) has been project partners representing interested parties for the knowledge transfer. There is presently an interest in creating a TW for post-tertiary treatment which also can be used a source of water for the refinery. Consequently, Gdańsk has served as a case study enabling scientific knowledge of the researches to be combined with practical and legal aspects of a TW in an urban landscape in a big city in the region.

3 RESULTS AND DISCUSSION

Based upon knowledge gained in the 3 workshops and a review of the scientific literature the following first recommendations for design can be presented.
The first part of the wetland system should consist of a HSSF. There are a number of important decision factors for this recommendation. The cold climate of the region is one of 4 important decision criteria for a recommending the first part of the wetland system to be a HSSF wetland. The Baltic Sea Region has a hemiboreal climate and temperature may be well below 0 ^{o}C during several months. As microbiological activity is important for many biological processes the variation of temperature will influence the overall performance of the wetland for the reduction of nitrogen and organic matter. The design and operation of a wetland in the Baltic Sea Region is therefore particularly challenging. HSSF and VFs have the advantage that water is not directly exposed to the cold atmosphere. Thus, energy losses through evaporation and convection are minimized [17]. Still, most HSSF wetlands in very cold climate will not be prevented from freezing by incoming water and an insulation layer is considered necessary and in practice in Minnesota it has been accomplished by adding 15 cm layer of mulch [9]. Other materials have also been suggested and one important aspect is that it should be substantially decomposed without the loading of additional organic material to the wetland system [18].

Another option would be, which is used for post-tertiary treatment in Sweden, to use a FWS wetland and accept the seasonal variation of reduction as can be observed for total suspended solids (SS) in Ekeby wetland, Eskilstuna during a 11 year period [19](*Figure 1*). This is possible in Sweden as discharge limits for organic matter and nitrogen are usually set as yearly averages. However, this was not found to be an option for the owners of the waste water treatment plant in Gdańsk as this type of discharge limits are unheard of in Poland. Thus we expect less seasonal variability of reduction in a HSSF system.

A second decision factor is the risk of exposure to pathogenic organisms in the wetland and this argument was raised on several occasions during the workshops by representatives from the local authorities and owners of the WWTP as the wetland system or part thereof should also be accessible and used for recreation. Of primary concern is therefore designing for removal of pathogenic organisms. Traditionally, the presence of pathogenic organisms in waste water has been monitored using specific groups of bacteria which indicate contamination of human faecal origin such as the number of faecal coliforms (FC) and the number of total coliforms (TC). Most information on the reduction of pathogenic organisms in treatment wetlands, have therefore been monitored using these. As indicator organisms also occur in wetlands in extremely varying numbers, reduction is usually reported as the reduction in the base 10 logarithm of indicator numbers [6]. Using this method, [9] recently evaluated the log10 reduction of FCs in 89 FWS and 76 HSSF wetlands for waste water treatment. The median value was 2.00 respectively 2.09 and the frequency distribution for the two wetland types showed a similar shape thus very little difference between wetland types

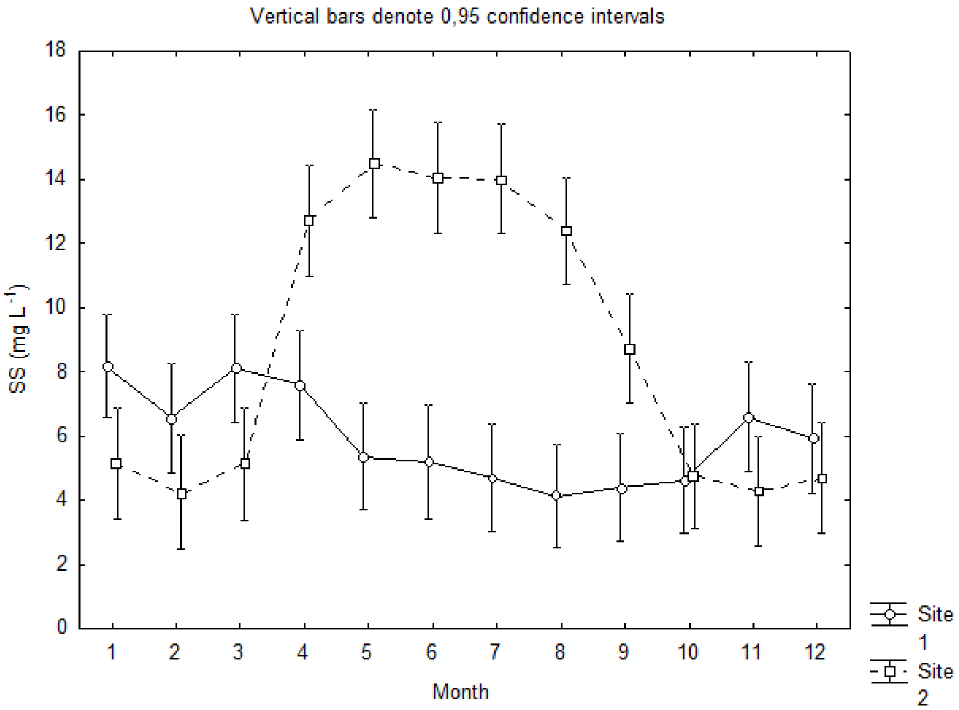

Figure 1. Total suspended solids (SS) in inflow (site 1) and outflow (site 2) of the Ekeby wetland during 2001-2011. The graph is an output of a 2-way ANOVA.

was observed. There are today a number of techniques for identifying and enumerating pathogenic organisms for example protozoan parasites like *Cryptosporidium parvum*, *Giardia lamblia* and *Toxoplasma gondii* in waste water and wetlands. Although there is not presently a large database enabling a comparison between the wetland types and efficiency of removal pathogenic organisms, several studies show that they can be removed to a large extent in filter beds in VF wetlands, HSSF wetlands or a combination of wetland types (i.e. hybrid systems). For example, [20] obtained a log10 reduction of 2 in a hybrid system for treatment of raw waste water.

There are also studies indicating a risk of introduction of pathogens from dogs and wildlife in FWS [21] and this may be considered a drawback for a wetland which is intended to be used for recreational purposes. It should be kept in mind that there are presently no studies, to our knowledge, quantifying the risk in HHSF wetlands and FWS wetlands or any study enabling the risk to be compared between wetlands for post-tertiary treatment of waste water and recipient waters used for swimming in the nearby area. Thus, more information is needed in order to make a scientifically based decision for recommendation but we opt for a HSSF wetland at the present time.

The third decision factor used for recommending a HSSF wetland as the first part of the wetland system is the high ground water level in the Gdańsk area in combination with the risk of salt water intrusion into the wetland as the WTTP is situated only a few km from the sea. Bottom isolation is therefore deemed necessary to prevent the dilution of the effluents and the contamination of ground water. This isolation will likely add to the cost of the HSSF which in general is more costly than an FWS wetland but cost also vary which parameters that will be reduced and to which extent they are reduced [9]. HSSF wetlands have in general no particular advantage in terms of space savings however, for tertiary BOD, denitrification and pathogen reduction HSSF area requirements is expected to be smaller [9]. He also points out that the main decision factor is often if authorities allow the waste water to be exposed to humans but as this wetland is for post-tertiary treatment it should be allowed, at least there is no inhibiting EU legislation to our knowledge. The next question that should be raised is then if a FWS wetland is operable under the climatic conditions. The Swedish FWS wetlands are operable under the climatic conditions but as described above the seasonal variation of reduction is high and during several winter months, reduction will be very low. This might prevent the WTTP owners to reach discharge limits imposed if these are based upon monthly values. In the Gdańsk case, GIWK owns a land area next to the WTTP where a HSSF wetland could be placed.

It is well known that HSSF wetlands are prone to clogging and there are Swedish experiences from treatment of landfill leachate where this has been observed. The potential economic consequences of this clogging may be considerable [9]. The risk of clogging should be smaller for post-tertiary treatment than for primary or secondary treatment of waste water still, there is a need for an in-depth case specific analysis of the risk and how it can be reduced but at the present time we recommend a system for removal of particles before treatment in the HSSF wetland. An additional benefit of particle removal before the HSSF wetland is that many persistent pollutants such as heavy metals and POPs are often associated with particular matter and these can then be collected in a small area of the system instead of being spread to the whole wetland system. In a recent study by [15] the hazard of sediments in a FWS wetland for treatment of landfill leachate in Sweden was determined using bioassays. This wetland has sediment traps at the inlet followed by 10 ponds and the ranking of the sampled toxicity of sediment indicate that the wetland system has a design facilitating the concentration of toxic substances in the sediment traps and the first pond. An evaluation of the removal of metals and metalloids in the wetland supports this observation [2,3].

When summarising the first decision factors and their consequences on design we therefore opt for recommending particle traps followed by a HSSF wetland as the first part of the wetland system. It should be part of the WTTP and the owners should be responsible for it. Discharge limits may be set for eutrophying substances, organic material and pathogenic organisms. The area can be fenced in but human and wildlife access should be limited by vegetation already present at the site such as reed (*Phragmites sp.*) and bulrush (*Typha sp.*). HSSF also lack the aesthetic value of FWSs and human presence is therefore expected to be limited. In a recent bird inventory at the site a wetland specialist was observed, the bearded tit, *Panarus biarmicus*. Its´ main habitat is large reed beds in brackish and freshwater environments and it´s therefore important to maintain its habitat in the area and limit access for humans and domestic animals.

No calculations for determining size of the HSSF wetland and reduction potential for nitrogen, organic material has been conducted so far but we suggest that the HSSF is followed by a FWS wetland system placed on brownfield areas and abandoned land owned by the municipality close to the WTTP. An important decision factor for this is to support ecosystem services beyond improvement of the effluent quality. Ecosystem services can according to [22] be divided into 4 categories; supporting, provisioning, regulating and cultural and they influence human well-being. Processes for primary production and nutrient cycling belong to supporting functions and if wetland plants are harvested and used as biofuels they also contribute to the provisioning ecosystem services. The water purification is part of the regulatory services and it´s expected that the FWS wetland will further improve the water quality beyond regulatory demands today (e.g. emergent pollutants such as pharmaceuticals). As discussed above FWS wetlands show a large seasonal variability of reduction making it difficult to set discharge limits on average monthly values. It would of course be desirable to use the system of yearly averages used in Sweden for TWs for post-tertiary treatment but this might be a lengthy legal process before it is implemented. Experiences from Sweden also points to smaller reductions of nitrogen than calculated values [19]. The Ekeby wetland in Eskilstuna is used for post-tertiary treatment and the variation of daily flow is substantial, resulting in a large variation of weekly and monthly flow and accordingly a variable retention time of water in the wetland. This is most likely due to treatment of storm water in the WTTP and maybe also to some extent to leaky pipes. Another factor is the low density of macrophytes such as reed and bulrush compared to many other TWs and we regard the water level to be too high for their successful colonisation. The wetland plants have been shown in many studies to be of great importance as attachment sites for denitrifying bacteria and organic material will fuel the denitrification process [23]. Furthermore, when the hydraulic loading (HLR) of the wetland is compared to other FWS analysed by [9] it becomes clear that with an HLR of 15-18 cm/day it belongs to the upper quarter of the 205 FWS wetlands studied. Considering the suggestions that oversizing of FWS might be necessary in cold climate [9,17] we simply might have overestimate the removal efficiency for nitrogen in FWS wetlands used for post-tertiary treatment in Sweden.

A wetland is expected to have longevity of decades thus it is also important to know if the wetland will remove pollutants in the long term in a predictable manner. An important characteristic of the Ekeby wetland is the high predictability of nitrogen removal for the range of HLR and nitrogen load during at least a decade of operation (*Figure 2*) thus, the expression “ticking like a clock” stated by the operator of Magle wetland in Hässleholm [24] is also valid for Ekeby wetland and no statistically significant change in nitrogen removal efficiency with age has been observed [19]. Similar results have been obtained for metal and metalloid removal in a wetland for treatment of landfill leachate [25].

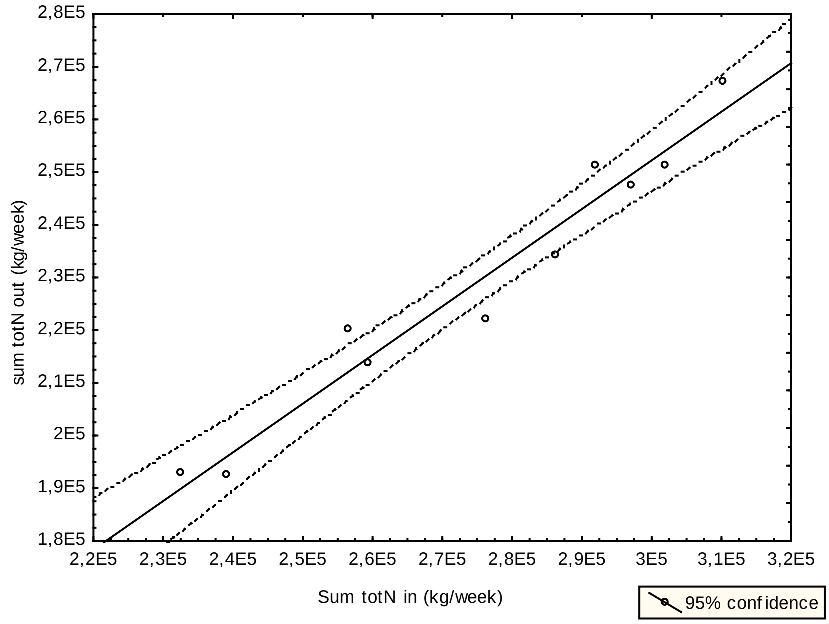

Figure 2. Linear relationship between nitrogen load into the wetland (sum of nitrogen load in/week during a year) and nitrogen load in the effluent from the wetland (sum of nitrogen load out/week during a year) during operation 2003-2012. Each dot represent one year, $R^2=0.94$

The fourth category of ecosystem service is cultural ecosystem services. In Eskilstuna and Hässleholm the FWS wetlands for post-tertiary treatment are located in the outskirts of the cities and they have been designed for recreation and education. Bikers and hikers are invited and provided with paths, information boards, pick-nick areas and observation towers for bird watchers and these are used both for recreation and educational purposes. By compartmentalizing and design improvements of the FWS wetland higher reduction is expected for several water quality parameters [9,18] and this will also contribute to create a diversity of habitats for the wildlife in and around the wetland.

In the analysis so far we have presented and discussed many direct and indirect benefits of a wetland including improved water quality, enhanced biodiversity and recreation in an urban landscape. However, potential problems beyond clogging in HSSF and the exposure to pathogenic organisms should not be ignored. Wetlands are for example known to be significant sources of important greenhouse gases including nitrous oxide and methane. However, in an analysis of agricultural landscapes in New England [26] suggest, in terms of ecosystem services, that the value of nitrogen removal services is greater than the greenhouse gas disservices incurred. In some areas mosquitos have been a problem but this has not been observed in Sweden or Estonia [26] nor have we in Sweden observed hydraulic short cuts due to the foraging and tunnelling activity of nutria and rats. Strong odours may also cause nuisance but this is normally not a problem in Sweden and Estonia [27].

In cities there may be a competition for land and it might therefore be difficult to find a site sufficient in size and suitable for the construction of a wetland close to a WTTP. However, in many cities in the Baltic Sea Region derelict land and brownfield areas are available, like in the Gdańsk case and the feasibility to treat both waste water and storm water in FWS in an urban landscape throughout the region should be explored. A final important question is who should bear the cost, when effluent quality beyond regulation is requested. One possibility is to sell the water for reuse. In an Italian example, the investment cost was reduce from 30 €/capita to 5 €/capita when purified water was sold for reuse [11, 28]. In the Gdańsk case a refinery owned by Grupa Lotos S.A. is situated close to the site of the WTTP. Today process- and cooling water is taken from the river Vistula but the water quality is not always acceptable (i.e. Si concentration is too high) and chemical treatment is therefore necessary before the water can be used [29]. An important next step is therefore to analyse the Si concentration in the effluents from the WTTP and calculate theoretical removal rates in the suggested wetland system. Implementing methods for estimating the value of ecosystem services in the EU may also in the future show the economic advantage of TWs in an urban landscape.

4 CONCLUSIONS

Constructed wetlands for treatment of effluents from sewage treatment plants have been shown to have multifunctional properties as they may reduce nutrients, persistent pollutants, indicator and pathogenic organisms in an effluent as well as support biodiversity in and around the wetland and our recommendations on designed presented in this paper are based upon these. The proposal includes a first part, which mainly will be focusing on pollutant and pathogen removal using particle traps and a HSSF wetland on land owned by the WWTP and a second part consisting of a FWS wetland which, in addition to further polishing the water, will enhance biodiversity and provide recreational areas on derelict land owned by the city.
There are clearly several challenges to be overcome in order to obtain the interest, acceptance and complete recommendations for creating wetlands for post-tertiary treatment of waste

water in the Baltic Sea Region. One challenge is the limited amount of space in urban settings requiring innovative solutions for sufficient treatment especially during cold periods. Another challenge is the high ground water level in many coastal areas of the Baltic region and the possible raising of the sea level in the near-by future due to climatic effects. Thus, it is of outmost importance to find solutions which protect the wetland from salt water intrusion and at the same time protect the ground water from being polluted. There has also historically been a resistance among engineers and politicians to employ constructed wetlands for waste water treatment in urban settings which remain to some extent still today because of assumed risks of odour nuisance or that the wetland will attract flies. As the wetlands often retain pollutants that cannot be biodegraded as heavy metals it also important to design the wetland so hazardous substances are accumulated where they can easily be excavated.

New eco-innovations should be an additional outcome of this project if WTTP owners, authorities and scientists work together in designing and testing pilot scale wetlands for WTTPs in realistic settings. For example, one or several methods for enhancing the performance reviewed by [18] may be explored as well as other new technical developments presently used for other applications by the participating scientist in this study.

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