MAGNETIC NANOPARTICLES AS A TREATMENT METHOD FOR WASTEWATER

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Abstract

Wastewater management and the need for clean drinking water is an unavoidable issue that societies have faced since the dawn of civilisation. The UN estimates that 380 trillion litres of wastewater is produced globally. Current methods of physical, biological, chemical and sludge treatment all have their associated disadvantages such as by-products or scalability.

Magnetic nanoparticles(MNPs) are an emerging technology that is already being researched in areas such as targeted drug delivery and the development of photothermal therapy that is commonly used to treat cancers. MNPs have the potential to be a breakthrough in wastewater treatment as a portable solution for remote areas or as a low-energy, sustainable and versatile alternative to current methods. These advantages of MNPs can be attributed to the low-energy extraction process with permanent magnets, the reusability of particles, and their ability to be specialised for specific contaminants.

1: Identifying the Current Issue

1.1: Background on waste water

Wastewater refers to water from households, businesses, and factories that enter sewage systems. The most common types of wastewater are greywater (from showering and laundry equipment such as showers, sinks and washing machines), blackwater (which comes from toilets), and industrial wastewater (wastewater that comes from businesses or factories).[1]

Wastewater is extremely harmful to humans and the environment as it contains pathogenic organisms such as bacteria and viruses that can cause disease. Wastewater also has a significant concentration of pollutants such as sediments which can cause waterways to be blocked[1], chemicals and heavy metals become extremely toxic to the environment when mixed with natural elements such as water, soil and air[2], and nutrients (primarily phosphorus and nitrogen) when it enters water bodies and can accelerate the growth of algal blooms that have negative implications on the ecology of the water body.[1]

1.2: Background on wastewater treatment

The history of water treatment methods dates back to 2000 BC when Greek and Sanskrit writings indicate that the civilisations were aware of purifying water through heating, and also had sufficient knowledge of sand and gravel filtration. The main motive for these filtration methods, however, was to ensure that drinking water tasted better. Turbidity (the clarity of a fluid due to the concentration of solutes) was the main factor that drove water filtration methods as not much was known about containment and micro-organisms.[3] Over thousands of years, wastewater filtration methods grew to be more complex incorporating emerging technologies as the standards for water became stricter and implemented in a multitude of countries.

Current solutions are insufficient for two main reasons; the volume of water and the significant levels of pollutants within the wastewater. Two economic factors that drive the research, production and implementation of these treatment methods are the significant investment capital and the high energy costs associated with the plant. For example, in a small community in Oceanside, California there is an old water treatment facility built in 1949, and the estimate of a replacement facility is $100 million (exclusive of the operational costs).[4] Another example of the high energy utilised by such plants is a quotation from the American Council for An Energy Efficient Economy where they stated, “Municipal water supply and wastewater treatment systems are among the most energy-intensive facilities owned and are operated by local governments, accounting for about 35% of the energy used by municipalities." This case study shows us the high energy consumption associated with current wastewater management and such energy consumption is bound to incur adverse environmental implications.

2: Current Solutions, Benefits and Limitations

2.1: Current solutions of water treatment

Managing wastewater using water treatment methods is a vital role that ensures safe and disease-free water is returned to the environment. Despite this, the volume of wastewater being generated has risen over time.[5] The United Nations (UN) predicts over 80% of wastewater enters the environment without adequate treatment. Current water treatment solutions include:

Physical water treatment

Physical water treatment refers to the separation and removal of contaminants through sedimentation, aeration and filtration. Sedimentation is the technique in which heavy solids and insoluble materials are allowed to settle at the bottom of the wastewater and can be easily removed through decantation (pouring off the pure water).[6] Aeration involves the circulation of air through the wastewater which promotes the biodegradation of the wastes. Then, special types of filters can be used to remove waste, with the sand filter being the most commonly used as it's flexible.[7] It can apply high pressures to wastewater and rapidly move it through the sand particles allowing them to catch contaminants due to their sharp edges as shown below in Figure 1.[7]

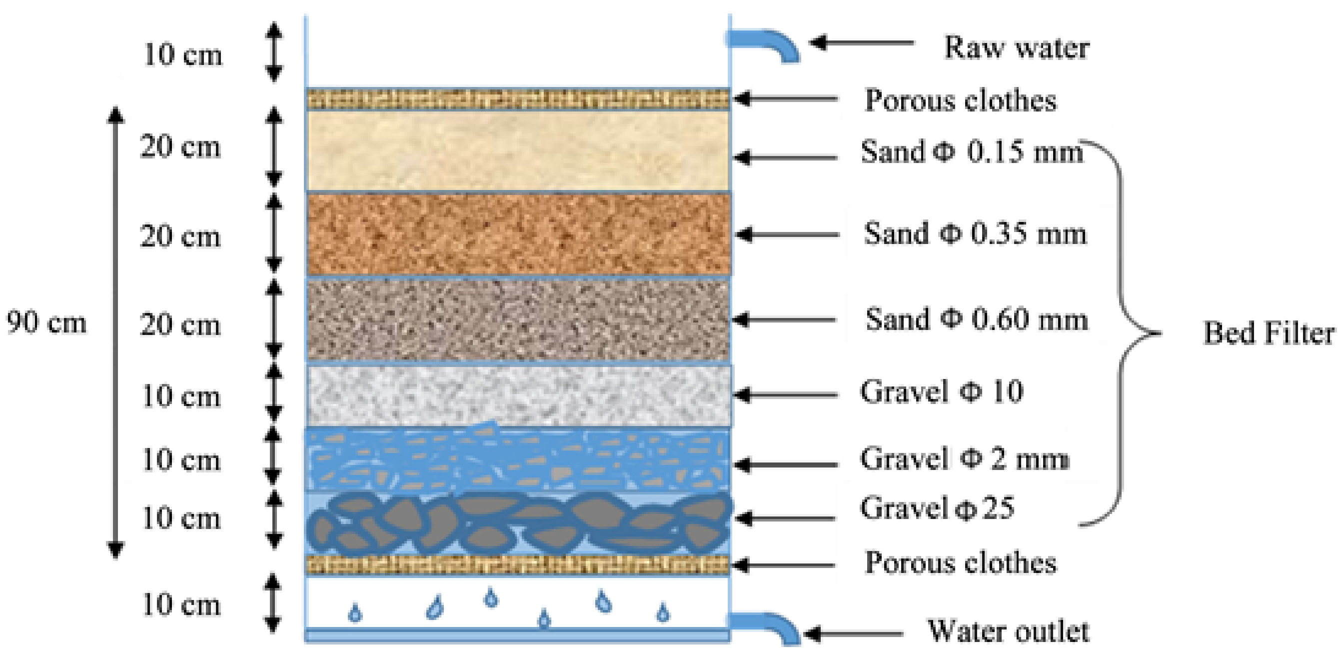

Figure 1: Diagram of the sand filtration system used in the low-cost filtration of domestic wastewater for irrigation purposes, produced by Sosthene KM.

Biological water treatment

Organic matter is frequently observed in wastewater and can include soaps, human excretions, oils and food. The metabolic property of microorganisms can be used to break down foreign compounds through three treatments. Aerobic processing involves the organic substances being decomposed through the bacteria's ability to utilise oxygen and convert the waste into carbon dioxide.[8] Anaerobic processing works similarly but is the fermentation of this organic matter often at a specific temperature to ensure proper removal of waste.[8] Composting is the final alternative to biological water treatment and is also an aerobic process, however, it is capable of reducing bulky waste into finer, soil-like particles containing nutrients and humus.[6]

Chemical water treatment

Through the presence of chemicals, wastewater can be disinfected, purified and so that its measure of acidity (pH) can be regulated. Chlorine is used to break the chemical bonds in the bacteria formed in the water and is an effective disinfectant.[9] Ozone is another method of chemical treatment and when injected into water, it can rapidly oxidise and remove contaminants, such as the elimination of bacteria, viruses and even metals such as cadmium, arsenic, lead and copper.[10] Neutralisation is the final process in which an acid or base is added to the water to neutralise the pH level to an accepted industrial standard to ensure it is safe for drinking standards after the addition of other chemicals.[6]

Sludge treatment

There are three main steps involved in sludge treatment which involves thickening, digestion and dewatering to remove contaminants. Thickening involves using large mechanical machines to thicken the sludge from its semi-liquid or dissolved state. This process requires the wastewater to undergo gravity settling, flotation or centrifugation.[6] Then, digestion can occur, which reduces the mass of solids and makes it easy for dewatering. Most sewage treatment plants use a two-step process using anaerobic digestion which allows enzymes to break down the matter at a specific temperature, pH, and acidity, among other factors. The remains are then dewatered, through using sludge-drying beds, leaving the residue behind. Dewatered sludge still retains a large amount of water (approximately 70%), but even with this moisture present, it can still be handled as a solid material as it doesn't behave as a liquid. The sludge is then sent to a landfill, incinerated or reused as fertiliser in agriculture.

2.2: Limitations of these solutions

Water Treatment Methods	Limitations
Physical Treatment	-Certain pollutants are difficult to remove and hence becomes less effective -Space required for its infrastructure is large and can lead to higher costs -High energy requirements as filtration and aeration will require a driver for the process to occur
Biological Treatment	-The process ‘aeration’ requires a large amount of electricity which in turn requires burning of fossil fuels to produce (creating greenhouse gases) -Solid waste needs to be disposed appropriately as it may cause algae overgrowth -Can produce microorganisms and odour that can alter the aquatic environment if its not appropriately removed
Chemical Treatment	-Chlorine’s disinfectant byproducts (DPBs) can be harmful to the environment, humans, and aquatic life -Expensive cost of sourcing chemicals, depending on the volume of wastewater and chemicals required
Sludge Treatment	-Inappropriate disposal of sludge (incineration or conversion to fertiliser) will have monetary and environmental consequences -Equipment required to thicken, digest and dewater the sludge will require a large amount of energy (electrical and mechanical)

3: Magnetic Nanoparticle Application in Wastewater Treatment

3.1 Background on magnetic particles

Magnetic nanoparticles (MNPs) are a type of nanomaterial known for their exceptional magnetic characteristics.[11] They are typically composed of magnetic substances like cobalt, iron oxide, or nickel, and have a size range between 1 to 100 nanometres.[12] Due to their distinctive properties, they find extensive applications in a variety of fields.[12]

3.2 Properties

Magnetic nanoparticles have a variety of differing properties due to their different structures and the method used for their production [11,12]; General properties of magnetic nanoparticles include high surface area to volume ratio, magnetism, catalytic activities, high reactivity, high mobility, and high adsorption capacities.[11,13] Additionally, magnetic nanoparticles can be functionalized with various molecules such as antibodies or enzymes to target specific substances or particles.[11] The unique combination of magnetic, chemical, and physical properties of magnetic nanoparticles makes them a versatile and promising material for a wide range of applications.[11-13]

MNPs can exert antibacterial effects through both physical and chemical means.[13] The magnetic feature of MNPs gives them an excellent separation property in the vicinity of an external magnetic field, which is essential for their removal after use.[11,13,14]

3.3 Uses

MNPs have a wide variety of uses in a range of fields from environmental science to medicine.[11,12] This is due to their unique properties which provide new and more effective ways of solving complex problems within these fields.[11,12]

3.3.1 Water treatment

Magnetic nanoparticles have been found to be an efficient tool for wastewater treatment, particularly for the oxidative elimination of micropollutants and microbial pathogens through the process of photocatalysis.[11,12] This process involves using UV lights and the MNPs to break down organic pollutants and microbial pathogens in water.[11,12] The MNPs absorbs the UV light and generate highly reactive species that can oxidise the pollutants, resulting in their degradation to harmless products.[11,12] Nearly 100% removal of various types of contaminants such as pharmaceuticals and personal care products, dyes, pesticides, and heavy metals have been achieved through MNPs.[11] This also gets rid of the need to add disinfectants like chlorine and ozone as the particles can be removed once the treatment has completed through the use of a magnetic field.[13,14]

3.3.2 Other applications

Application	Description
Biomedicine	Magnetic nanoparticles can be used in a range of biomedical applications, such as targeted drug delivery, magnetic resonance imaging (MRI), hyperthermia treatment, and bio separation.[12] They can be designed to specifically target cancer cells, allowing for more effective treatment with fewer side effects.[12]
Energy storage	Magnetic nanoparticles can be used in energy storage applications, such as rechargeable batteries and supercapacitors.[15] They can improve the performance of these devices by increasing the surface area and facilitating electron transfer.[15]
Catalysis	Magnetic nanoparticles can be used as catalysts in various chemical reactions.[12] They can increase the rate of reaction by providing a large surface area and allowing for better control over reaction conditions.[12]
Food industry	Magnetic nanoparticles can be used in the food industry to detect contaminants and improve food safety.[12] They can be functionalized with specific chemical groups to bind to particular contaminants, making them easier to detect and remove.[12]

3.4 Production

There are many ways in which MNPs can be produced, each producing a slightly different type of MNP with their own benefits and demerits.[11,12] The synthesis of MNPs can be classified into three primary methods: physical methods, chemical methods, and biological or microbial methods each of which are more effective for different uses.[11,12]

3.4.1 Physical methods

Physical methods for producing MNPs often come with high energy investments and use processes such as vaporisation, grinding, etc to produce nanoparticles.[11,12]

Ball milling method

Ball milling is a top-down method for producing MNPs, The method is relatively crude and involves the grinding of rough particles into fine nanoparticles.[11,12] The main disadvantage of this process is the contamination of the produced particles. The particles produced have a wide size distribution compared to other methods.[11,12]

Laser evaporation

Laser evaporation is a bottom-up synthesis method where the material of choice is submerged in a liquid solution, a laser beam is then fired through the liquid which evaporates the material producing a gas.[11,12] This gas is then rapidly condensed, and due to this rapid condensation, the material forms as nanoparticles. This method produces high quality MNPs but is not very cost effective due to the high energy investments and is unsuitable for large-scale production.[11,12]

3.4.2 Chemical methods

Chemical methods typically involve bottom-up approaches where MNPs are produced often through a reduction or oxidation reaction.[11,12] These methods are usually costly and difficult to scale up, however can offer greater control over the size and shape of the product.[11,12]

Co-precipitation method

The co-precipitation synthesis method of producing MNPs involves reacting iron hydroxide in an aqueous monophasic liquid at high temperatures.[11,12] This method produces MNPs with less control over particle size compared to other chemical methods.[16 (p2)] The method also uses relatively safe chemicals compared to other methods and is able to produce large quantities of MNPs, though it is quite expensive.

Sol-gel method

The sol-gel method produces metal oxide nanoparticles through the hydroxylation and condensation of a molecular precursor of the target MNP. Throughout the reaction, the solution is homogenised with a nano disperser and aged which causes particle formation and then a metal oxide network which forms the ‘gel’.[16(p2)] The ‘gel’ then undergoes a drying process, an annealing treatment and finally powdered which produces the desired nanoparticles.[16 (p1)] This process offers great control over size and shape, but is costly, and requires a time consuming, high energy process.[16(pp2,3)]

3.4.3 Biological or microbial methods

Biological/Microbial syntheses of MNPs makes use of living organisms such as plants and microorganisms.[11,12] The MNPs produced in this method are biocompatible and are very useful in the biomedicine field, this synthesis method is very efficient and produces little waste products while being the cheapest of the three approaches.[11,12] This approach however is still in early development stages and has great potential to be scaled up whilst still producing consistent, low defect batches of MNPs.[17(p2)]

3.5 Extraction and recycling

Magnetic nanoparticles are able to be reused many times before losing effectiveness and the method used to recycle the particles makes use of zero chemicals that could potentially cause contamination.[14] The magnetic nanoparticles are first extracted from the water through a method called magnetic separation, this process involves exposing the water to an external magnetic field which attracts the magnetic particles while not affecting the water and causing the two to be pulled apart.[14] The magnetic nanoparticles are then able to be cleaned through many processes such as cold plasma treatment where the magnetic nanoparticles are exposed to plasma under low temperatures to remove the attached contaminants.[18] Other methods include the use of microfluidic techniques which show extremely high cleaning efficiencies of up to 99.7%.[19(pp1,7)]

4: Benefits of Magnetic Nanoparticle Water Treatment

4.1: Specialisation

It is important to make a distinction between clean water and potable water and that water treatment does not only involve the removal of all contaminants to produce pure water. Pure distilled water is unsafe for human consumption because of its tendency to absorb minerals and salt from the human body. This means a solution's ability to target certain contaminants but not others is an advantage for producing potable water.

An advantage of nanoparticles in general is that they can be specialised to target certain contaminants. This involves changing either the nanoparticle composition itself or using coatings for the surfaces of nanoparticles.[20(p4)] Polymer coatings specifically, due to their ability to be engineered to attract different substances according to the functional groups present, can serve as an effective method to specialise magnetic nanoparticles for a variety of different contaminants.[20(p4)]

4.2: Low energy cost

The extraction method simply involves exposing the magnetic nanoparticles to a magnetic field so it is possible to use permanent magnets, which means there is no energy requirement for extraction. A study has found that even the crudest method with only a hand-held permanent magnet achieved 80-85% extraction efficiencies.[21(p6)] However, current extraction efficiencies are currently too low for drinking water requirements partially due to magnetic nanoparticles being a new technology.[21(p6),22(p539)] With further research, it is possible for small scale versions of the process to serve as a portable solution which can be used in remote areas without electricity.

4.3: Reusability

Nanoparticles can be reused as they extract contaminants physically unlike chemical water treatment which involves chemical reactions between the contaminant and the treatment agent.[22(p522)] As there are no chemical reactions, there is no consumption of nanoparticles and the particles may be washed and reused. This significantly lowers costs compared to chemical treatment methods which consume its cleaning agent whilst being more sustainable.

4.4: Versatility

Advances in magnetic nanoparticle technology not only benefit wastewater treatment but also a variety of other fields. Magnetic nanoparticles potentially serve in medical applications such as in MRI imaging or cancer treatment due to their special properties. MRI imaging relies on nuclear magnetic resonance which implies that magnetic nanoparticles may serve as a contrast agent to produce sharper images.[23(p15)] The magnetic properties combined with specialisations can allow magnetic nanoparticles to treat cancer by using an external magnetic field to heat up the nanoparticles to induce localised hypothermia to the tumour.[23 (p19)]

5: Current Limitations and Further Research

5.1: Current limitations

Although magnetic nanoparticles pose as a potential miracle solution to reusing more waste water. Current technology for magnetic nanoparticles for water treatment, still has glaring issues which affect its practicality. However, new research is also being put out, showing great promise for overcoming these limitations.

5.2: Extraction efficiency

Low extraction efficiency is currently a barrier to the use of magnetic nanoparticles in drinking water treatment due to the current inability to remove enough nanoparticles to produce potable water.[21(p6)] However, iron concentrations of magnetic nanoparticle treated water is acceptable for use in industrial applications.[21(p8)]This current limitation is largely due to magnetic nanoparticle water treatment being a relatively unexplored area, and the inconsistencies in nanoparticle shape and size for cost-effective production methods.[16(p2)]

Today, new methods of extraction which allow higher flow rates whilst being more efficient are being discovered. One of these being the MagNERD system, which is able to handle continuous flow and at an extraction efficiency higher than hand-held magnet methods whilst using only permanent magnets.[21(p6)] However, the efficiency is still not high enough for drinking water though developments are being made to improve the MagNERD.[21(p6)]

5.3: Overcoming viscosity

The efficiency of extraction for magnetic nanoparticles are greatly affected by the viscosity of the fluid it is treating. In order for extraction to be possible, magnetic force on nanoparticles within a solution must overcome the viscosity in order to be extracted. As the viscosity of wastewater varies greatly depending on its source, starch and oils contaminants for instance greatly increases the viscosity, this can produce inconsistent extractions and poor results.

Our understanding of magnetic force and drag on nanoparticles is rapidly improving. It is known that in low velocities, drag force is approximately proportional to the radius(~r) of the particle whereas magnetic force is proportional to volume (~r^3).[24(p3)] There is likely an effective compromise between maximising surface area by decreasing the size of nanoparticles and having enough magnetic force to overcome viscosity which benefits from increasing the size of nanoparticles.

There is also the case that the effect of magnetic fields on nanoparticles brings largely unexpected effects with space for more discoveries. Research is being conducted on the effect of size and shape of particles as at the scale of mere nanometers, the attractive strength of a magnetic field becomes more complex due to the significance of surface effects as a greater proportion of atoms reside on a particle's surface.[23(p7)] For instance, some non-magnetic materials in bulk, like platinum, are known to show ferromagnetic effects at the nanoparticle scale. Whilst iron oxide nanoparticles show decreased ferromagnetic effects, some materials like cobalt are shown to have increased ferromagnetic effects as a nanoparticle.[23(p7)] Potentially, a certain combination of size, geometry, and material allows the particles to be less affected by viscosity and have a stronger response to magnetic fields.

5.4: High production costs

Another limitation facing the use of magnetic nanoparticles is that consistency in size and shape is required for water treatment but this leads to the need for high cost production methods. The current methods for producing magnetic nanoparticles have to leverage control over high costs. Many chemical methods such as the Sol-gel method offer great control over size and shape of particles however it is a multiple day process as well as being costly.[16(pp2,3)] Other methods such as chemical co-precipitation is cheaper but carries the drawback of producing a wide range of nanoparticle sizes.[16(p2)] Another approach is using physical methods such as the ball milling methods or laser evaporation. Ball milling is cheap but produces a variety of sizes and laser evaporation offers greater control over size but is far more expensive and limited to small scale applications.[11,12]

One alternative being researched today is the use of bacteria for the production of magnetic nanoparticles. The use of bacteria theoretically allows precise control while potentially being suitable for large scale applications, and cheap due to no high energy investment like physical processes or large chemical investment.[25(p301),17(p2)] A study has shown the technique of using Fe(III) reducing bacteria can produce consistent sized nanoparticles for target sizes 5-90nm for a variety of materials.[17(p1)] The study also briefly investigated which factors in bacterial fermentation production of nanoparticles affect the particle size. Potentially, with further research into controlling nanoparticle size within production, using bacteria to produce magnetic nanoparticles may be a cheap and large-scale method for making the magnetic nanoparticles required for water treatment.

5.5: Chemical reactivity

The high surface area which makes nanoparticles remove contaminants faster also makes potential chemical reactions between the contaminants and particles faster as well. One such reaction for Magnetite(Fe_3O_4) NPs is oxidation with acids and bases.[20(p15)] This contributes negatively to performance degradation and extraction efficiency.

This may be resolved case by case through the use of different materials for the nanoparticles. However, there is the strict requirement for magnetic properties which limits the materials which may be used for the core of the particles. Magnetic properties are known to vary wildly when applied to the nanoscale due to the significance of surface effects.[23(p2)] New research into the effect of magnetic fields on different materials may unlock new potential materials that may be used for water treatment that are less reactive.

6: Research Considerations and Data Collection

6.1 Research funding

In order for our team to continue their investigations into the viability and efficiency of magnetic nanoparticle technology within the field of wastewater treatment, we require appropriate funding to further our research. Such finances will be directed towards expeditions to various developing countries to determine the composition and toxicity of wastewater samples, equipment and materials required for data analysis and the acquisition of magnetic nanoparticles. As to increase the scientific reliability and validity of our data, our team has planned to collect 13 samples from sewage plants in the cities of Dar-es-Salaam, Dakar, Lusaka and Visakhapatnam. These sites were chosen specifically by our team due to the inefficient treatment of wastewater in their plants and facilities.[26] The magnetic nanoparticles to be used in our research and experiments will be sourced from CD Bioparticles. Our estimations predict the net costs of the project to total around $282,950, owing to the purchasing of magnetic nanoparticles, funding of expeditions, staff payroll and lab equipment.

6.2. Ethical considerations

When conducting research in which the collection of samples is required, it is often necessary to travel to various countries to ensure that your data analysis is relevant to your proposed implementation of your research . However, this has begun to become a point of contention and controversy within the scientific community, with many members expressing the concerns that the relevant benefactors involved within these research projects may be left unacknowledged. As our team will be working side by side with industry professionals throughout our expeditions, we will be able ensure that staff members are appropriately credited in our project by contacting the sewage plants we intend to partner with. Furthermore, for each country that our research team visits, a section of our paper will be dedicated to the culture and land, as well as recognising the local citizens who may have assisted our activities.

6.3. Collection of samples

Our team is aiming to partner with Sukita Sewage Ponds, the Manchinchi Wastewater Treatment Plant, Station d'épuration Onas Step Camcerene and the Gvmc Sewage Treatment Plant to collate data regarding the effectiveness and efficiency of the current wastewater management implemented which allows us to compare with the magnetic nanoparticles. This expedition will also be beneficial in discerning how this new technology could be implemented within these facilities. These samples are to be chosen by our team through systematic sampling techniques in order to ensure increased reliability of our project. Working alongside these plants, we as a team strive to acknowledge the efforts of foreign residents on our work.

6.4. Practical issues with real world wastewater plants

The issue of treating excess wastewater has been a largely growing problem facing many developing countries across the globe. While the process of safely disposing and irrigating wastewater has improved significantly in many nations, many countries fail to keep up with the rising costs and management associated with the technology, ultimately resulting in the pollution of important bodies of water. In fact, an approximate 80% of wastewater sourced from countries of varying income brackets flow untreated into the environment.[27] 50% of sanitation within low income countries do not include the treatment of wastewater, which starkly contrasts against the 15% rate of a nation such as the U.S.[28] Furthermore, of the 50% of existing plants, many fail to thoroughly treat wastewater, often involving processes involving only one or two steps. Wastewater and faecal sludge are a large source of pathogen cultivation and pose a significant threat of disease dissemination towards these countries. Biological pollutants affecting local bodies of water in developing countries pose significant health threats against the young and elderly. Waterborne pathogens such as giardiasis and amebiasis are cultivated through the presence of untreated faecal matter. Such diarrheal diseases comprise 4.1% of the total global disease burden, resulting in an approximate 1.8 million deaths annually.[28] Moreover, pollution of local bodies of water can have devastating impacts upon surrounding ecological systems. The culmination of pollutants as a result of untreated wastewater can lead to high levels of nutrients such as nitrogen and phosphorus, which can induce algal blooms.[29] These lower the quality of the water they occur in, killing off fish and other aqueous species. A large majority of diverse coral reefs on earth are clustered near tropical, developing countries. Due to inefficient sanitation systems, massive amounts of raw wastewater are being discarded onto these reefs, hampering growth and reproductive rates. [26] We believe that with sufficient research, magnetic nanoparticles have the potential to be a large-scale and affordable option for countries around the world.

7: Conclusions

The prevailing issue of treating wastewater has faced humanity ever since the implementation of sewage systems within Mesopotamia, providing a humanitarian and ecological threat that must be alleviated in the near future. Giving way to the cultivation of biological hazards that endanger the aquatic wildlife and livelihoods of inhabitants in developing countries, the need for an accessible and cost effective form of wastewater filtration is at an unprecedented high. Hence, our team proposes that the research into the burgeoning technology of magnetic nanoparticles is a highly important and viable endeavour in finding a solution to this global issue. Currently, there are a vast array of methods being used to filtrate wastewater around the world to varying results. Many of these are inefficient in removing the biological toxin component in wastewater, while the other more complex and developed technologies are too costly in their management and production to be viable in poorer regions.

Magnetic nanoparticles have an extremely low energy usage in the process of treating wastewater, significantly driving down its operational costs compared to competing methods. Furthermore, these particles aren't consumed within the procedure, leading to reduced chemical waste and making the technology more accessible to developing nations. This technology is additionally able to target particular contaminants in water due to its high level of specialisation. The potential list of this technology's benefits could further improve through further research and appropriate funding. Our team believes that magnetic nanoparticles are the future for accessible and effective wastewater sanitation methods.

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