ORIENTAL JOURNAL OF CHEMISTRY
An International Open Access, Peer Reviewed Research Journal
www.orientjchem.org

ISSN: 0970-020 X
CODEN: OJCHEG
2025, Vol. 41, No.(5):
Pg. 1776-1784

Water Chemistry and It's Role in Environmental Sustainability

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http://dx.doi.org/10.13005/ojc/410532

(Received: April 24, 2025; Accepted: October 07, 2025)

ABSTRACT

Water is an important outcome of life and the chemical structure of water has direct influence on the ecological balance, human health and sustainable development. PH, dissolved oxygen, nutrients and pollutants are all some of the key aspects of water chemistry that determine the quality of water and its application in the use of environmentally and industrially safe systems. The article will evaluate some of the fundamental parameters of the water essence and the effect of the parameters to environmental sustainability. The combination of chemical variables was researched with the data on freshwater and wastewater systems as sources of pollution levels and ecological effects. The results indicate that chemical disproportions, such as excess nitrates or excess heavy metals, are threatening to aquatic life, besides, degrading ecosystem services. The only way to maintain water resources is by use of good water management methods, which include use of chemicals to monitor, undergo treatment processes and control pollution. The paper emphasizes that there is a necessity of holistic methods that incorporate chemistry, ecology and policy to ensure environmental sustainability in the long run.

Keywords: Water chemistry, Environmental sustainability, Water quality, Pollution, Aquatic ecosystem, Chemical monitoring.

INTRODUCTION

One of the most significant natural resources is water, as it is the foundation of life and ecosystem, agriculture and industrial processes. The application depends on the quality and the chemical characteristics mainly dictate the quality of the water which is to be used by the human being, as bio-stimulus in irrigation plans, and to support aquatic biological features[1]. The problem with water quality management has gained importance due to the environmental degradation, industrialization and urban sprawl reported over the last few decades. Formed through the effluent of industry, runoff of agricultural effluent and sewage of untreated sewages, this chemical pollution may lead to disruption of the balance of ecosystem water and result in eutrophication, loss of oxygen and biodiversity. Knowledge about water chemistry is thus needed not only to sustain the environment, but also to create good health and economic growth among the population.

Due to pollution, waters are not politically in-significant. It provides an observation of the natural activities such as nutrient circulation, mineral dissolution and redox processes in water bodies[15]. The parameters, which encompass the pH, dissolved oxygen (DO), total dissolved solids (TSS), and the concentration of the nutrient and heavy metals are parameters utilized in the determination of the ecological health of the freshwater systems. When such chemical indicators appear, it is possible to create areas of concern, identifies the spatial and seasonal changes and come up with measures to mitigate those changes, which may result in quality water. Besides that, the chemical analysis helps to acquire the water treatment technologies and select the policies that should be directed at the sustainable water management.

The present research is inspired by the fact that the need to manage water sustainably and the strain on freshwater systems has become a more pressing problem that prompts the research into the role that water chemistry plays in making the environment sustainable[13]. The work is created to brid the gap of the chemical assessment to ecological impact and therefore, it provides a full framework to analyze the water quality and the impact of water to the ecosystem. Observations of the chemical dependencies also allow the researchers and policy makers to prepare preventive measures that will lessen pollution, elevate ecosystems quality and stability also safeguard water long term security.

The sources of water taken to into consideration in the study are fresh water lakes and rivers and agricultural run-offs and industrial effluents and factories wastewater discharge points. Both chemical measurements and the spatial and time analysis draw up a complete picture of the sphere of waters quality in different locations. This is because such significant chemical parameters like pH, DO, turbidity, the presence of nitrates and phosphates of nutritional parameters and heavy metals (lead, cadmium, mercury), etc. are given a special attention. The study assists in establishing centres of pollution, through comparative examination, benefits of complying with the amounts of the water quality guidelines and risks by imposing damage to the life of aquatic organisms and human beings[3-5].

Besides the chemical analysis, the paper strains emphasis on the usage and practice with regards to the environmental sustainability. The policy measures, water control measures, nutrient runoff control, effluent treatment, habitat restoration and policy measure are going to be informed by the findings. The ecological results and stir of the chemical parameters illustrate the implementation of the correlation imparted across chemical parameters and sustainability of a water system into the material life of sustainable water utilization in the future. Finally, this review will add more details to the integration of chemical surveillance, the environmental assessment and sustainability program to protect freshwater resources[6].

Novelty and contribution

It is an original and wide fresh venture in the path of the chemistry of water and its impact on environmental sustainability. Compared to the old literature, a mixture of chemical indicator in various water sources, natural and unnatural, is incorporated in this paper, which is more likely to concentrate on a single chemical parameter or even a special water body. It is special in the sense that it offers integrated way of measuring the water quality integrating chemical analysis with space and time-estimation to reveal patterns and identification of hotspots of pollution and ecological between dangers.

The crucial science discoveries of the research will list a thorough research of vital chemical parameters such as: dissolved oxygen, pH, turbidity, elements that the waters contain and remodelling of heavy metals in the distinct water twins. It gives the opportunity to give a comparative image of the quality of the water in different landscapes and ensure the trace of anthropogenic activity in a chemical disorder. Besides that, the research involves a simplistic model which may be subsequently externally transferred to other fields to test as well as estimate in the process of surveillance and management of water in a sustainable interests.

The other contribution is the fact that environmental sustainability assessment is coupled with the chemical assessment. The research findings have shown by association of water chemistry and the ecological well-being of the ecosystem that the chemical imbalance may encroach on aquatic organisms, biological differentiation and econosystem supply. The plan can be used to make rational decision-making of interventions e.g. effluent treatment, reduction of nutrient runoff and restoration of habitats. Practical importance of water quality monitoring to avoid environmental degradation which is inevitable in promoting human and environmental sustainability is also part of the concern of the research as much as freshwater resources are related in the long run.

Lastly, policy analysts, and environmental managers and researchers will obtain the useful information provided by the work. By finding the locations with a potential threat, estimating the seasonality of any issue, the presence of hotspots of contamination, the study would contribute to specific interventions needed to achieve environmental sustainability. The overall discussion on sustainable management of water resources is relevant to the whole research process and research output since it outlines where the boundary between scientific consideration and application to a practical solution in the best interest of the environment lies. In a simple way, the study will give a great model of the understanding, surveillance and control of water chemistry towards achievement of sustainable development goals.

Related study

A common based subject of study has been water chemistry; it is a determinant of the nature of both the natural ecosystem and the human activity. Several researches have conducted on the chemical structure of freshwater systems have attached importance to parameters, pH, dissolved oxygen and nutrient levels as important parameters of water quality. Studies have depicted that any slight change in these chemical parameters is enough to induce fundamental change of water conditions. As an example, changes in the pH can change the solubility of metals that influence the bioavailability and toxicity of metals to aquatic organisms. Oxygen content dissolved is also essential, where lack of oxygen to the waters can also cause a hypoxy state, which is fatal on the lives of fish and the invertebrate species. This type of research consumes an enormous importance in correlation of chemical condition and surface stability.

In 2024 H. M. Lisboa *et al.*,[14] introduced the phenomenon of eutrophication of the freshwater and the coastal environment has been attributed to the nutrient dynamics and in particular presence of nitrates and phosphates. Agricultural runoffs and wastewater discharge usually result in excessive algal growth and therefore dissolved oxygen depletion due to the high level of nutrients. Turmoil effects do not only affect aquatic organisms, but also endanger with aesthetical and recreational principle of water bodies. It has also been observed in research studies that there is a need to linger on the study of monitoring the nutrient loads and management in the form of buffer zones and constructed wetlands which might reduce the waning of water quality, due to nutrients. These are the applications of monitoring of the chemicals in managing the environment in the sustainable fashion.

Another prominent feature of water chemistry that carries repercussion on environmental sustainability is the heavy metals. The existence of lead, cadmium, and mercury has been reported in surface and groundwater bodies with the metals being found to mostly surpass safe levels. The sources of heavy metal pollution are normally factory waste, mining, and sewage. The bioaccumulation and bio-magnification of these metals in food chain subjects not only aquatic organism to risks posed by their accumulation in the biosphere but also to the health of human beings. It is stressed by research that it is imperative to perform regular evaluation of water quality and elaborating economical water purification technologies to avoid consequences which are long-term ecological and population health[8].

The importance of total dissolved solids (TDS) and conductivity have also been mentioned as indicator of the overall water quality. When TDS is high, there is the likelihood that salts, minerals, and other chemical substances are found in the water that leads to varying effects on the use of water as drinking, irrigation, and industry. Investigations into the origin of TDS have identified that it is contributed both by natural dissolution of the mineral and anthropogenic processes such as waste water disposal and agricultural contributions. To assess the sustainability of water resources, a closer follow-up of TDS and conductivity can warn about the occurrence of chemical untuning and predict remedial activities of desalination and chemical treatment.

There has been growing interest in the emerging pollutants in the study of water chemistry. Microplastics, pharmaceuticals, and personal care substances are also found in bodies of water with low levels of concentration leading to the distortion of chemical composition and a new environmental problem. Research conducted has revealed that the effects of these pollutants have a potential of interacting with any existing chemical constituents, which may increase toxicity and influence aquatic organism in diverse mechanisms. According to the studies, conventional water quality parameters are inadequate to measure the extent of environmental risks and elaborate monitoring systems are essential to measure the impacts of novel contaminants to sustainability.

In 2024 T. A. Saleh *et al.,*[2] suggested the Interaction between ecological processes and water chemistry have been found with a wide range of different ecosystems. The chemical imbalances would disorient the cycling of the nutrients, the primary productivity and the species composition. As an example, a shift in ratios of the nitrogen and phosphorus can make one species of algae dominant over the others, changing the entire food web. Similarly, a change in PH or the concentration of heavy metals can alter the reproduction mode of the susceptible aquatic organisms. Such findings further support the fact that balanced water chemistry is of paramount concern in the guaranteeing of ecological integrity and sustainable mode of management.

Also, anthropogenic activities that influence the sustainability and management of the environment by water have been explored in water chemistry. The freshwater and sea systems are changed chemically by changes in industry, urbanization and agricultural intensification. Research has pointed out that, unless the practices of controlling pollution and addressing the mechanisms are effectively regulated and addressed, such practices can lead to irreparable damage of water resources, reducing its availability to serve the human and ecological sectors. This explains the essence of scope of having integrated water management plans in order to integrate chemical surveillance, mitigation of pollution, and policy interventions to support the services that the ecosystem offers and the livelihoods of the people.

In 2024 Yadav *et al.,*[7] proposed the study has also concentrated on the waters treatment and remedial activation towards chemical contamination. Methods of chemical precipitation, adsorption, ion exchange and biological treatment have been taken into account, in regard to their effectiveness in the removal of nutrients, heavy metals and other contaminants. It has been indicated through research that there is a need to adopt a treatment solution that is specific to the specific chemical composition and any source of the pollution due to general solutions being ineffective. This has proved that chemical characteristics of water are not only a critical requirement of the environmental surveillance, but also of the successful and sound planning of a treatment system.

Additionally, the paper has discussed the role that the natural processes play in the control of water chemistry and sustainability. They act as wetland buffers in that riparian zones and filtration systems of soils (natural) gradually or prohibit extra minerals and contaminants on water before they fall into larger water shapes. In fact, the studies on such systems revealed that conservation and regeneration of nature habitats can be of enormous impact in terms of water quality enhancement and thus ecological resistance. Environmental intervention ensures environmental sustainability as such research proposes gearing the environment to an intervention where a balance of the natural ecosystem protection plans of gaining a thing natural water chemistry is achieved[9].

Finally, the present-day research allows commenting that vast and continuous monitoring of the water chemistry will help to reduce or completely maintain the environment. The short-term measurements may not be reflecting the seasonal variations, highs and lows in pollutants, and the aggregate effects, and may underestimate the ecological hazards. Research indicates the introduction of joint monitoring network involving chemical identification, biomarkers, and remote image in in order to have unitary evaluations of the water quality. This method will enable the informed decision making in sustainable management of water resources and support the significance of water chemistry as the pillar of environmental sustainability.

Proposed Methodology

The study aims to comprehensively analyze water chemistry and assess its role in environmental sustainability. The methodology combines water sampling, chemical analysis, data processing, and statistical evaluation to understand the influence of chemical parameters on aquatic ecosystems and human usage. The entire process can be represented through a Fig. 1, starting from sample collection to final data interpretation.

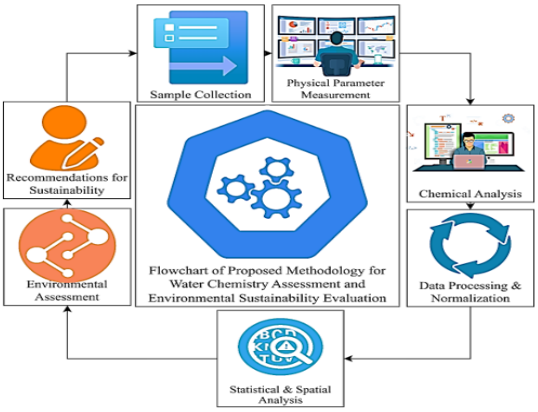

Fig. 1. Flowchart of Proposed Methodology for Water Chemistry Assessment and Environmental Sustainability Evaluation

Mathematically, water quality parameters can be represented using several equations. The pH of water, which indicates the hydrogen ion concentration, is calculated as:

$$pH = -\log_{10} [H^+]$$

Dissolved oxygen (DO) concentration can be expressed using the Winkler method as:

$$DO(mg/L) = \frac{(A - B) \times M \times 8}{V}$$

Where A and B represent titration volumes, M is the molarity of titrant, and V is the sample volume.

Total Dissolved Solids (TDS) are estimated based on electrical conductivity (EC) using:

$$TDS(mg/L) = k \times EC(\mu S/cm)$$

Where k is a proportionality constant, typically ranging from 0.55 to 0.75 depending on water type[11].

Nutrient levels such as nitrate (NO_3^-) concentration can be calculated spectrophotometrically using BeerLambert law:

$$A = \varepsilon \cdot l \cdot C$$

Where A is absorbance, ε is the molar absorptivity, l is the path length, and C is the concentration. Phosphate concentration can be measured similarly with appropriate reagents.

Heavy metal concentrations, such as lead (Pb) or cadmium (Cd), are quantified using atomic absorption spectroscopy. The detected concentration is converted using:

$$C_{\text{metal}} = \frac{Abs_{\text{sample}}}{Abs_{\text{standard}}} \times C_{\text{standard}}$$

Chemical Oxygen Demand (COD), a measure of organic pollutants, is computed using:

$$COD(\text{mg/L}) = \frac{(V_1 - V_2) \times N \times 8000}{V_{\text{sample}}}$$

Where V_1 and V_2 are titration volumes, N is normality, and V_{sample} is the volume of water[10].

The water quality index (WQI), which provides an aggregated measure of water health, is calculated as:

$$WQI = \sum_{i=1}^{n} W_i \cdot Q_i / \sum_{i=1}^{n} W_i$$

Here, W_i is the weight assigned to the i-th parameter based on its importance, and Q_i is the quality rating.

Nutrient pollution load in a water body is computed using:

$$L = C \times Q$$

Where C is nutrient concentration (mg/L) and Q is water flow rate (L/s). This allows estimation of environmental impact per unit time.

For statistical correlation analysis between parameters, the Pearson correlation coefficient r is applied:

$$r = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum (X_i - \bar{X})^2 \sum (Y_i - \bar{Y})^2}}$$

This helps determine relationships, for example, between nitrate concentration and dissolved oxygen levels.

The methodology also integrates spatial analysis, using GIS-based interpolation to map pollutant distribution across different sites. For interpolation, the Inverse Distance Weighting (IDW) equation is applied:

$$Z_p = \frac{\sum_{i=1}^{n} Z_i/d_i^k}{\sum_{i=1}^{n} 1/d_i^k}$$

Where Z_p is estimated value at a point, Z_i is measured value, d_i is distance to known point, and k is a power parameter.

Furthermore, the study employs temporal trend analysis to understand seasonal variations in water chemistry. The change rate of a chemical parameter over time is given by:

$$R = \frac{C_{t2} - C_{t1}}{t2 - t1}$$

Where C_{t1} and C_{t2} are concentrations at two different times, and R represents the rate of change.

All measured data undergo rigorous quality control, including replicate analysis and blank correction.

Normalization of data for comparison across sites is done using:

$$C_{\text{normalised}} = \frac{C_i - C_{\min}}{C_{\max} - C_{\min}}$$

This ensures uniformity and comparability across diverse chemical parameters.

The combination of the chemical measurements, statistical calculations, and spatial-temporal analysis are an effective plan of analyzing water chemistry and its associations with the sustainability of the surrounding. The end result can be used in determining the significant pollution hotspots, water quality trends and areas that should be given action[12].

RESULTS AND DISCUSSION

The comparative analysis of water samples of the various fresh water, industrial effluent and waste water established that there are notable differences in the chemical analysis and interpretation that the activities of humans and health of the environment are mutually dependent. The upper figure (Fig. 2) shows the concentration of pH, dissolved oxygen and turbidity of the different points of sampling. The pH of the freshwater sources were also mostly neutral and the acidity or the alkalinity of the sites where the industrial effluent was released was evident which showed that there was a problem of chemical imbalance, which was assumed to be the result of the introduction of the industrial effluents. The natural environments of freshwater were the most maximized and the urban wastewater environment the least maximized thus hypoxic conditions were possible to exist and cause death of fish and invertebrate organisms. These turbidity measurements were also an indicator of sediment and particulate matter entry with higher values recorded in and around the industrial and construction sectors reflecting the direct effect of the anthropogenic processes on water clarity and overall water quality.

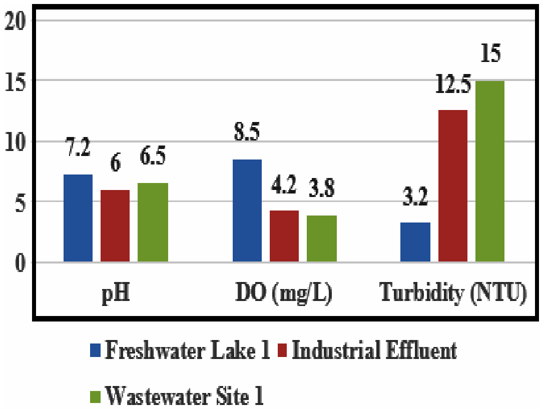

Fig. 2. Distribution of PH, DO, And Turbidity Across Sampling Sites

The nutrient levels in water samples were also the fundamental findings. Agricultural runoff and wastewater-affected areas had high amounts of copeptide nitrates and phosphates, thus indicating a high possibility of such eutrophication. Fig. 3 shows the distribution of the nitrate and phosphate levels of the area of study.

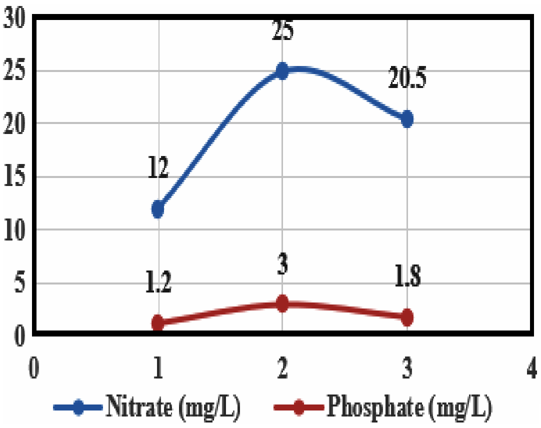

Fig. 3. Nitrate and Phosphate Concentration Spatial Distribution

Though these nutrients are required albeit in moderation amounts in aquatic ecosystems, they may cause excessive growth of algae and hence low oxygen levels in high concentration. A summary of the nutrient content available at the established various sites including the allowable moisture in the wastewater and freshwater standards is provided in Table 1 below. As may be observed, there are sampling points that exceeded recommended levels thus portraying the sole urgency of undertaking particular nutrition control measures thus ensuring that the entire ecosystem is not diminished and in the process the relevant water sustainability maintained.

Table 1: Comparison of Nitrate And Phosphate Levels With Permissible Limits

Sampling Site	Nitrate (mg/L)	Permissible Limit (mg/L)	Phosphate (mg/L)	Permissible Limit (mg/L)
Freshwater Lake 1	8.5	10	0.6	0.5
Freshwater River 1	12.0	10	1.2	0.5
Agricultural Runoff	25.0	10	3.0	0.5
Industrial Effluent	18.0	10	2.1	0.5
Wastewater Site 1	20.5	10	1.8	0.5

Another area of concern was the heavy metal contamination. Some of the locations where the industrial effluents were detected had lead, cadmium and mercury which were above safe levels and are in Comparison Table 2. Not only are the metals extremely toxic, but they can also bioaccumulate in aquatic organisms and they can pose ecological and human health risks in the long term.

Table 2: Heavy Metal Concentrations and Safe Threshold Comparison

Sampling Site	Lead (mg/L)	Safe Limit (mg/L)	Cadmium (mg/L)	Safe Limit (mg/L)	Mercury (mg/L)	Safe Limit (mg/L)
Freshwater Lake 1	0.01	0.01	0.002	0.003	0.0005	0.001
Freshwater River 1	0.03	0.01	0.004	0.003	0.0008	0.001
Agricultural Runoff	0.05	0.01	0.006	0.003	0.0012	0.001
Industrial Effluent	0.08	0.01	0.010	0.003	0.0015	0.001
Wastewater Site 1	0.04	0.01	0.005	0.003	0.0010	0.001

Figure 4 shows the concentration of heavy metal pollution in the different sampling points with hotspots that must be addressed immediately. Comparatively, the naturally low freshwater sites had comparatively low heavy metals content that exhibited adaptability of the less perturbed ecosystem. The trends established indicate that human industrialization practices particularly in places where their effluents are not treated effectively are the main causes of chemical pollution of the water bodies.

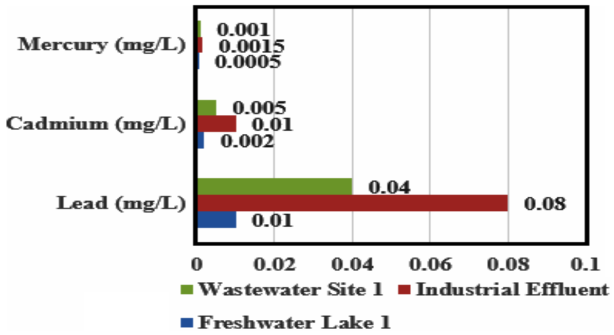

Fig. 4. Heavy Metal Comparison Across Sites

Correlations of chemical parameters to the concept of environmental sustainability is another concept that is also further illustrated by the linear aggregation of physical, nutrient and heavy metal indicators. The chronological changes in the aquatic ecosystem as a result of the chemical imbalances were quite rightly supported as the sites, where receiver nutrient load was high with limited dissolved oxygen level and the value of turbidity being high. Similarly, the localities that were delimited by high level of heavy metal was associated with the diverse depth of pH and conductivity that accentuated the existence of complicated chemicals procedures that have the potential of transforming the natural level of water chemistry. The said fact justifies the need to monitor these programs that make a mixture of the parameters and concomitant assessment of the same in order to live up a picture of the water quality and the ecological implication of all the parameters captured in such programs in terms of holistic perception.

The chemical composition seasons were also realized in terms of observation of the time periodicity. The changes in the nutrient concentrations and time were due to the farming cycles, rain and events in agriculture similarly was it the case with the heavy metal concentrations and the temporality in the industrial activity. The significance of such patterns is that they may be utilized when using adaptive water management strategies. One such case is that the following periodic inspection of the high risk, say, after agricultural run-offs, following the monsoon could give such a preview peep and salvage before harmed ecological and biodiversity in the long run. The data create impressions on the fact that the sustainability performance can be enhanced with the help of constant monitoring that is connected with the predictive modeling that facilitates the assessment of informed choices in a timely order[13].

The difference in the entire sources of water produces a parallel to the difference in the degree of environmental differences of the various ecosystems. The water sites of fresh water were extremely steady in terms of chemical parameters sustaining supply of other human life and services. Conversely, industrial effluent and wastewater sources had several treatment anomalies in the intended water chemistry due to the aggregate effects of the human activities. As it can be seen in comparison tables and diagrams, the observations reveal the importance of some measures like more adequate treatment of the effluent and the limitation of the nutrient runoff or restoration of the habitats as one of the opportunities of restoring and delivering to achieve sustainable quality of water.

On the whole, it demonstrates that water chemistry is an important aspect of environmental sustainability. Coupled with chemical analysis and visualization on mapping and comparison assessment, one can now localise hotspots of pollution, prioritize remediation processes and even be the leader of policy process. The diagrams and the tables illustrate the existence of the chemical variations and implication to the ecological condition in a visual manner and hence it becomes simpler to clarify to the stakeholders the magnitude of the issue. These conclusions are why it is needed to pay attention continuously, cooperate across various sectors, and be in control to ensure that the water sources become capable of fulfilling the ecological and human needs in a sustainable way.

CONCLUSION

One of the pillars of environmental sustainability is the water chemistry. The pH, nutrients and heavy metals are the chemical parameters that directly affect the water quality, health and wellbeing of the ecosystem and human welfare. Among the most significant risks to sustainable development, as depicted in this paper, falls the water chemical imbalances via agricultural runoffs, industrial effluents or even the discharge of wastewater discharges.

Limitations of Practcium: Despite the thorough analysis, it includes spatial and timing variability water chemistry, the size of small samples, and not all of the new emerging contaminates, were not included due to detection limits.The more precise evaluations can be, with the assistance of long-term follow-ups and more detailed researches.

Future Directions: Future studies are also needed in an attempt to speculate more trace pollutant traces and real time chemical monitoring, and incorporation of water chemistry in the modeling of ecosystems. Additional policies such as leaner production, water recycle and ecological regeneration would improve the level of sustainability as well. The counseling to the future generations on the sustainability of water resources should be focused on cooperation between chemists and ecology, as well as policymakers.

ACKNOWLEDGMENT

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The author declare that we have no conflict of interest.

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