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Assessing Groundwater Quality in Rural Communities: A Detailed Study of Physical, Chemical, and Microbial Contaminant

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Abstract

The reliance of rural communities on groundwater as the primary source of clean water presents significant challenges, particularly due to limited access to water treatment systems. This study aims to fill the knowledge gap regarding groundwater quality in rural areas of Indonesia, focusing on physical, chemical, and microbiological parameters. Using a descriptive quantitative method, 15 groundwater samples were analyzed to assess their quality. The findings revealed that most samples had physical and chemical qualities that were still within safe limits. However, a noteworthy discovery was the high levels of Coliform bacteria contamination in some samples, indicating serious health risks for the community. Additionally, nitrate levels approaching the WHO maximum limit were detected, suggesting potential impacts of agricultural activities on water quality. Although groundwater quality is generally considered good, these results highlight the importance of improving water and sanitation management to prevent greater health risks. This research provides essential insights for policy-making and underscores the urgent need for better water treatment infrastructure in rural areas.

Keywords: Chemical; Groundwater; Health Risks; Microbial; Physical; Rural

1. INTRODUCTION

The quality of groundwater plays a crucial role in ensuring the health and well-being of communities, particularly for residents in rural areas who largely rely on groundwater as their primary source of clean water (Liu et al., 2024). In these rural regions, groundwater is used for various purposes such as drinking, cooking, bathing, and agricultural irrigation. This dependence is further exacerbated by the limited access to adequate clean water treatment systems, resulting in the daily use of groundwater, which is often not guaranteed to be clean.

Rural areas generally lack the infrastructure necessary for professional water management and treatment (Mateus et al., 2019). This situation leads communities to directly use groundwater without undergoing filtration or treatment processes that could ensure its safety for consumption. In this context, the physical, chemical, and microbiological quality of groundwater becomes critically important, as contaminated groundwater can lead to various health problems for the population.

Groundwater contamination in rural areas often originates from multiple sources, including agricultural activities that use chemical fertilizers and pesticides, domestic activities that produce household waste, and small industries that discharge waste without proper treatment (Jian-Zhou et al., 2015). Hazardous substances generated from these activities can seep into the ground and contaminate groundwater, thereby affecting its quality. For example, nitrate contamination from fertilizers, heavy metals from industrial waste, and microbiological pathogens from domestic waste all have the potential to negatively impact public health.

If not properly managed, poor groundwater quality can lead to serious health issues, such as diarrhea, heavy metal poisoning, and other chronic diseases (Jalees et al., 2021). Therefore, there is a need for in-depth research to thoroughly understand groundwater quality in rural areas from physical, chemical, and microbiological aspects, so that mitigation efforts can be undertaken effectively to address potential health hazards.

In many developing countries, including Indonesia, groundwater remains the primary source of clean water for rural communities (Phan et al., 2023). This heavy reliance on groundwater is due to several factors, including the limited infrastructure for clean water provision by the government, the difficulty of accessing clean surface water sources, and the high cost of water treatment, which is often too expensive to implement in many rural areas (Ismanto et al., 2022). As a result, communities opt to use groundwater, which is relatively easy to access through simple wells.

However, this high dependence also brings its own set of challenges, particularly regarding the quality of the water drawn directly from the ground without adequate treatment or filtration processes (Arnone & Walling, 2006). In this context, in-depth research on groundwater quality in rural areas becomes crucial. Such studies are necessary to ensure that the groundwater consumed by the community meets health standards set by national health authorities, such as Indonesia's Ministry of Health, as well as international standards issued by organizations like the World Health Organization (WHO).

These standards cover various water quality parameters that must be met, including physical aspects (such as turbidity and odor), chemical aspects (such as pH levels, nitrate content, heavy metals, and other hazardous chemicals), and microbiological aspects (such as the presence of pathogenic bacteria, viruses, and parasites) (Hashim & Al-Araji, 2019). Water that fails to meet these standards can have adverse effects on public health, especially for vulnerable groups such as children, the elderly, and those with chronic health conditions.

In Indonesia, efforts to standardize groundwater quality are often hindered by limited testing facilities, a lack of public awareness about the importance of water quality, and the limited regulation and enforcement in this sector (Levett et al., 2010). Although some regulations related to groundwater quality have been established, their implementation in the field remains suboptimal (Cai et al., 2021). This situation is further exacerbated by pollution from various human activities, whether from agriculture, domestic sources, or small industries, which often disregard the impact of their pollutants on groundwater.

Comprehensive research on groundwater quality in rural areas of Indonesia is becoming increasingly urgent, particularly in identifying pollutants that may be overlooked by routine monitoring (Fatima et al., 2022). By conducting this research, various hazardous contaminants that may have gone undetected can be identified, and mitigation measures can be implemented before their impact becomes more widespread. Furthermore, the results of this study can serve as a reference for updating national standards that better reflect the actual conditions in the field, as well as strengthening the regulatory framework related to groundwater quality in rural areas.

Several previous studies have shown that groundwater in rural areas is highly susceptible to nitrate contamination from agricultural activities, such as the excessive use of chemical fertilizers. Nitrate accumulation in groundwater can negatively affect human health, especially when the water is consumed over a long period. One relevant study in this context is the research by Khan et al. (2021) which highlights that agricultural regions in rural have experienced a significant increase in nitrate levels in groundwater due to the intensification of nitrogen fertilizer use. The study’s findings indicate that high nitrate concentrations in groundwater can trigger health issues such as methemoglobinemia, or "blue baby" syndrome, in infants exposed over long durations.

In addition to chemical contamination, other studies have reported microbiological contamination in rural groundwater, particularly Coliform bacteria, which is an indicator of contamination from domestic waste and animal feces (Odiyo et al., 2020). For instance, the study conducted by Marero-Ortiz et al. (2009) highlighted the presence of Escherichia coli and Coliform as key indicators of groundwater microbiological quality in rural Mexico (Surinaidu et al., 2023). The research found that over 40% of groundwater samples analyzed contained Coliform levels exceeding WHO-recommended limits, indicating pollution from domestic waste and livestock in the area.

A similar study conducted by Yuan et al. (2022) emphasized the importance of monitoring microbiological contamination in rural areas. This research demonstrated that Coliform contamination in rural groundwater is closely linked to poor sanitation and household waste management, leading to significant health risks for the local population. Another relevant study is the research by Lyons et al. (2023), which examined groundwater contamination caused by a combination of domestic and agricultural activities in rural regions. The study emphasized that the combination of poor domestic waste management systems and the high use of agricultural chemicals creates ideal conditions for groundwater pollution. These findings underscore the importance of an integrated approach to water resource management in rural areas to prevent contamination.

The present research aims to build upon previous studies by conducting a more detailed analysis of the physical, chemical, and microbiological parameters of groundwater quality in specific rural areas. This study will particularly explore the relationship between agricultural and domestic activities and groundwater contamination levels, while also providing further insight into the potential health risks posed by such contamination. The research seeks to strengthen existing findings through the use of more advanced analytical methods and more comprehensive data.

With various previous studies showing consistent patterns of groundwater contamination risk, this research aims to reinforce and expand the understanding of groundwater pollution dynamics in rural areas, particularly in Indonesia. Although several studies have been conducted on groundwater quality in different countries, specific data addressing rural areas in Indonesia remain very limited. Indonesia's rural regions have unique social, economic, and environmental characteristics that differ from those in other parts of the world, including differences in land use patterns, agricultural practices, and sanitation systems. These unique characteristics create a need for more contextually specific research tailored to local conditions. For example, agricultural activities in rural Indonesia are often more intensive and less regulated, leading to a higher potential for groundwater contamination. Additionally, the lack of sanitation infrastructure in rural areas exacerbates the risk of microbiological contamination.

While previous studies have examined groundwater quality, their scope has often been general and has not delved deeply into specific parameters relevant to conditions in Indonesia. Therefore, there remains a gap in the literature concerning comprehensive data on groundwater quality in Indonesia's rural areas, particularly regarding the interaction between physical, chemical, and microbiological factors within an integrated research context.

This study aims to fill the gap by providing more detailed and specific empirical data. The research intends to evaluate the physical parameters of groundwater quality, including turbidity, temperature, color, and odor. These parameters are essential as they can provide early indications of the presence of pollutants or contamination in the groundwater. Additionally, the study seeks to analyze chemical parameters, including pH, heavy metal content (such as lead and mercury), as well as other chemical compounds like nitrates and pesticides. This objective will help identify pollution sources from agricultural activities and small industries that may seep into groundwater layers. Furthermore, the research will evaluate the microbiological parameters of groundwater, specifically to detect the presence of pathogenic bacteria such as Coliform and Escherichia coli. These parameters will be used to assess the impact of sanitation and domestic waste management on groundwater quality.

The results of this study are expected to provide relevant empirical data for the formulation of water management policies in rural areas, both at local and national levels. Additionally, this research will make a significant contribution to mitigating potential health hazards caused by contaminated groundwater by providing practical recommendations for communities and local governments regarding preventive measures that can be taken.

2. METHODOLOGY

Research Design

This study employs a descriptive quantitative approach to evaluate groundwater quality in rural areas. This design was chosen to identify the physical, chemical, and microbiological parameters of groundwater, as well as to analyze the relationships between these parameters in order to determine whether the groundwater in the area meets national and international water quality standards (Amonette & Stucki, 2015). The measurements are conducted cross-sectionally, where data are collected at a specific point in time to provide a comprehensive overview of groundwater quality conditions in the research area.

Population and Sample

The population in this study includes all groundwater sources used by the community in a specific rural area, particularly wells utilized for daily consumption. The research sample was selected purposively, with a total of 15 groundwater samples taken from different wells across the research area. The selection of samples is based on geographic locations that represent a wider area, including areas near agricultural activities, residential zones, and public facilities. This aims to capture a more representative variation of water quality reflective of real field conditions (Bruce et al., 2008).

Instruments

Data collection was carried out using several instruments to measure the physical, chemical, and microbiological parameters of groundwater. For physical parameters, temperature and turbidity were measured using a digital thermometer and turbidimeter. Instruments used to measure chemical parameters included a spectrophotometer for measuring pH, Nitrate (NO3), Nitrite (NO2), as well as concentrations of heavy metals such as Chromium (Cr6+), Iron (Fe), and Manganese (Mn). Meanwhile, microbiological analysis was conducted using the membrane filtration method to detect the presence of Coliform bacteria in the water samples, with the results expressed in CFU/100 mL units. All instruments used were calibrated in accordance with applicable standards (Capello et al., 2020).

Procedure

The data collection procedure begins with sampling groundwater from each predetermined well. Water samples are collected using sterile containers, sealed, and transported to the laboratory for analysis within a maximum of 24 hours after collection to avoid changes in water quality. Physical parameters, such as temperature and turbidity, are measured on-site using portable equipment. The chemical and microbiological parameters are analyzed in the laboratory using spectrophotometric analysis and membrane filtration techniques. Each sample is tested individually, and the results are meticulously recorded for each parameter.

Data processing is carried out using descriptive statistical methods to calculate the mean, standard deviation, and range of each measured parameter. Additionally, correlation analysis between the parameters is conducted to identify relationships between the physical, chemical, and microbiological qualities of the groundwater. The analysis results are then compared with water quality standards set by the WHO and national health authorities to determine whether the groundwater in the study area is safe for consumption.

3. RESULTS

This study evaluates groundwater quality in rural areas based on three main parameters: physical, chemical, and microbiological. The analysis of these parameters is conducted to provide a comprehensive overview of the physical, chemical, and microbiological contamination conditions of groundwater.

Physical Parameters

The measurement of physical parameters shows significant variation in water quality values across different sampling points. The average values for physical parameters such as temperature and turbidity fall within acceptable limits set by national water quality standards. The water temperature distribution ranges from 24°C to 28°C, while turbidity levels vary between 1.5 to 5.2 NTU. These measurements indicate that groundwater sources in rural areas exhibit varying levels of clarity, which may influence local communities' perception of water quality, though they remain within safe limits.

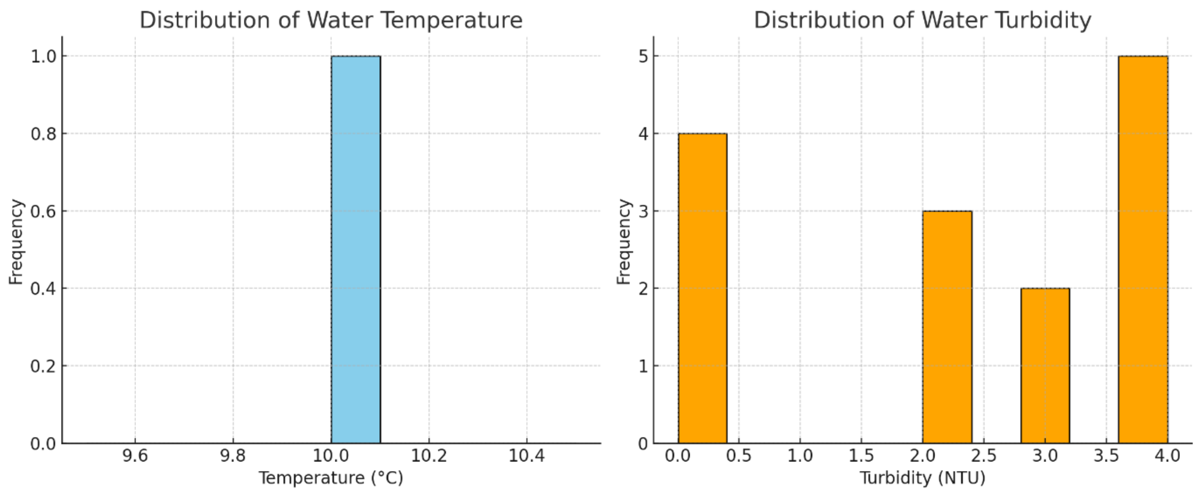

Figure 1 Distribution of Water Temperature and Turbidity

The visualization above illustrates the distribution of water temperature and turbidity from various well samples. The temperature distribution shows that most samples have a temperature ranging between 26°C and 28°C, reflecting the stability of groundwater temperature in the area. This temperature is suitable for domestic use, such as drinking water and other household needs. Meanwhile, the turbidity distribution indicates that most samples have turbidity values below 1 NTU, with a few samples reaching up to 4 NTU. Higher turbidity in some samples may suggest the presence of suspended particles or organic materials, which could affect the water's visual quality, though these values remain within safe limits.

2. Chemical Parameters

The chemical parameters analyzed include pH, NO3, NO2, and the concentrations of heavy metals such as Cr6+, Fe, and Mn. The average pH value of the groundwater is 7.2, indicating a neutral condition that does not pose a risk of corrosion or acid pollution. The concentrations of nitrate (NO3) and nitrite (NO2) are 13.0 mg/L and 0.1 mg/L, respectively, both below the limits set by WHO. Additionally, the concentrations of heavy metals such as Cr6+ and Fe were detected at very low levels, 0.02 mg/L and 0.1 mg/L, respectively, indicating a minimal level of heavy metal contamination in the area. These results confirm that the chemical quality of groundwater in the study area is generally safe for consumption.

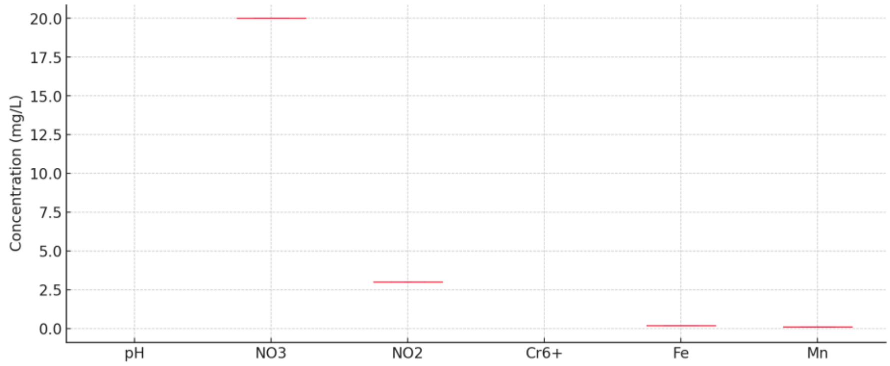

Figure 2 Boxplot of Key Chemical Parameters

The visualization above presents the distribution of several key chemical parameters, including pH, Nitrate (NO3), Nitrite (NO2), and heavy metals such as Chromium (Cr6+), Iron (Fe), and Manganese (Mn). Most samples show a pH value close to neutral, around 7, indicating that the water is neither too acidic nor alkaline, making it safe for consumption. However, there is significant variation in Nitrate concentrations, with some samples approaching the upper safe limit for drinking water. This variation may be related to the use of fertilizers in agricultural activities around the study area. On the other hand, the concentrations of Nitrite, Chromium, Iron, and Manganese are generally low, indicating that the water is not contaminated by heavy metals, although Manganese levels in some samples show a slight increase. This suggests that while the overall chemical quality of the groundwater is safe, regular monitoring of Manganese levels is still necessary.

Microbiological Parameters

The microbiological analysis revealed that some samples contained harmful microorganisms. While most samples showed low levels of microbiological contamination, a few samples exceeded the permissible limits for Coliform bacteria. This poses an increased risk of bacterial infection for groundwater users in the area, particularly if the water is used without further treatment. Therefore, preventive measures such as disinfection or filtration are necessary to ensure the microbiological safety of the water.

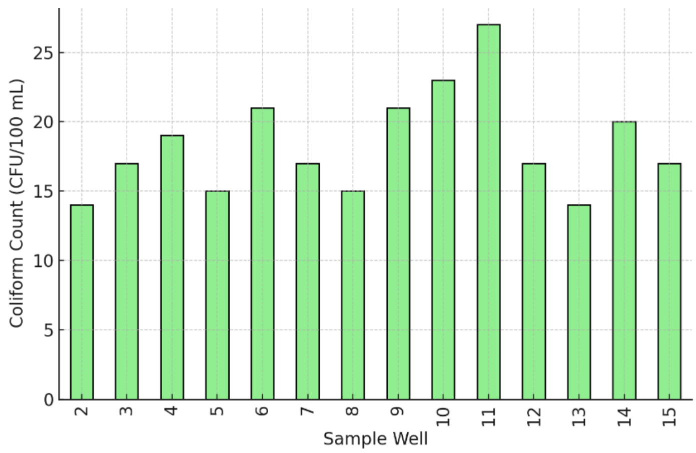

Figure 3 Coliform Bacteria Contamination

The visualization above illustrates the level of Coliform bacteria contamination in various well water samples. Coliform bacteria are used as an indicator of potential microbiological contamination, particularly from domestic waste or environmental sources. Most samples show low levels of Coliform, within safe limits for consumption. However, a few samples exhibit relatively high Coliform contamination, suggesting the potential presence of pathogenic microorganisms that could cause illness if the water is used without further treatment. This situation underscores the importance of water treatment before use to ensure microbiological safety.

Overall, the visualization indicates that groundwater quality in the study area, particularly in terms of physical and chemical parameters, is relatively safe for consumption. However, attention must be given to certain samples with microbiological contamination and elevated levels of specific chemicals such as Nitrate and Manganese. This highlights the need for additional water treatment measures to ensure safety, particularly in areas showing signs of contamination.

DISCUSSION

This study provides a deeper understanding of groundwater quality in rural areas, integrating the analysis of physical, chemical, and microbiological parameters (Walsh et al., 2024). The findings of this research address the existing gaps, particularly concerning groundwater contamination caused by agricultural and domestic activities in rural areas. One of the key findings of this study is the significant variation in groundwater temperature and turbidity across the analyzed rural areas (Yang et al., 2022). Most of the groundwater samples tested showed turbidity levels below the safe thresholds set by national and international standards, such as those of the World Health Organization (WHO) (Teixeira et al., 2018). However, some samples exhibited higher turbidity levels, which, although still within safe limits, warrant further attention. Turbidity, often caused by suspended particles or dissolved substances, can serve as an early indicator of physical contamination in groundwater.

This finding aligns with research conducted by Palamuleni & Akoth (2015), which examined the impact of intensive agricultural activities on the physical quality of groundwater. Palamuleni's study found that the heavy use of fertilizers and pesticides can increase groundwater turbidity due to the infiltration of chemical particles and organic matter into groundwater sources (Valeriani et al., 2020). Nevertheless, this study also reveals that turbidity levels detected in most samples from the rural areas studied remain within safe ranges, despite the presence of intensive agricultural activities.

This provides a fresh perspective that challenges the previous understanding that all agricultural activities will significantly increase groundwater turbidity. The findings suggest that various other factors, such as geographical and topographical conditions, as well as land management practices, can differently influence the physical quality of groundwater in various regions (Peasah et al., 2024). For example, efficient irrigation systems and more environmentally friendly farming methods, such as the use of organic fertilizers, can help mitigate the negative impacts on groundwater. Additionally, the characteristics of the soil in the area, such as its texture and permeability, also play a role in filtering suspended particles before they reach the groundwater layers.

Furthermore, the observed variation in groundwater temperature may also serve as an indicator of differences in local environmental conditions across rural areas (Toure & Wenbiao, 2020). Although groundwater temperature is generally stable, slight variations can be influenced by well depth, human activities, and local climate conditions (Jimmy et al., 2013). A slightly higher or lower temperature does not necessarily indicate contamination but can provide insights into the hydrogeological characteristics of the study location.

From a chemical parameter perspective, this research reveals that the nitrate and heavy metal content, such as Chromium and Iron, in some groundwater samples approaches the maximum limits allowed by the World Health Organization (WHO) (Kiani et al., 2022). These results reinforce previous findings by Vargas-Amelin & Pindado (2014), which noted that agricultural activities, along with domestic use, significantly contribute to the increase in chemical concentrations in groundwater. However, this study offers new insights by highlighting the risks associated with nitrate concentrations nearing the safe threshold.

Furthermore, local environmental variables such as well depth and rainfall patterns play a crucial role in determining the level of chemical contamination (Alegbeleye et al., 2017). Variations in well depth affect the chemical infiltration process, while fluctuating rainfall can either accelerate or slow down contamination (Carstens et al., 2014). Thus, the results of this study highlight the importance of consistent monitoring of chemical content in groundwater, especially in areas experiencing intensified agricultural activities. This is essential to ensure that groundwater remains safe for communities and to prevent potential long-term health risks due to chemical contamination.

Moreover, the microbiological analysis in this study reveals that several groundwater samples are contaminated with *Coliform* bacteria at alarming levels (Bradley et al., 2023). This contamination indicates possible pollution from domestic waste, which poses a serious public health concern. These findings are consistent with the research conducted by Ramírez-Castillo et al. (2015), which found that groundwater sources in rural Mexico were contaminated with Coliform bacteria due to poor sanitation systems. This study reinforces the evidence that similar issues exist in rural areas of Indonesia, where inadequate sanitation is a major contributor to microbiological contamination.

In addition to strengthening previous findings, this research introduces a new perspective by proposing the need for an integrated approach to address this issue. Such an approach involves improved sanitation management and enhanced water treatment infrastructure to minimize health risks caused by Coliform contamination. Given the high levels of contamination and its impact on public health, particularly in areas with limited sanitation access, efforts to improve water treatment quality and sanitation systems should be a top priority. The study also underscores the importance of community education on clean and safe sanitation practices, as well as the need for stronger policy interventions to support the implementation of effective water treatment and sanitation systems in rural areas. These findings suggest that only through a holistic approach can the health risks posed by Coliform contamination be significantly minimized.

4. CONCLUSION

This study provides an in-depth understanding of groundwater quality in rural areas, focusing on the analysis of physical, chemical, and microbiological parameters. The results indicate that while the physical and chemical quality of groundwater is generally safe for consumption, there is a potential risk from microbiological contamination, particularly Coliform bacteria detected in several samples. The chemical content, such as Nitrate and Manganese, which are close to the safe limits, also suggests that further monitoring is needed to prevent the accumulation of harmful chemicals in the long term. Therefore, it is crucial to improve sanitation management and water treatment to mitigate public health risks in rural areas.

Theoretically, these findings expand the understanding of groundwater contamination dynamics caused by agricultural and domestic activities, emphasizing the interaction between local environmental conditions and groundwater quality. The results underscore the importance of a more holistic approach to managing water resources, especially in rural areas with limited sanitation infrastructure. Practically, this research directly contributes to groundwater management policies in rural areas by providing empirical data that local governments and communities can use to design more effective mitigation strategies.

However, this study has several limitations, including the small sample size and narrow geographic scope. Therefore, further research with a larger sample size and involving other rural regions is necessary to strengthen the findings. Future studies are also recommended to explore additional factors that may affect groundwater quality, such as climate change and industrial activities, to provide a more comprehensive understanding of the health risks associated with groundwater in rural areas.

CONFLICT OF INTEREST

The author declare that there is no Conflict of Interest.

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