Review

A Review on Water Quality Indices

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Received: 30 January 2025; Accepted: 6 March 2025; Available online: 10 March 2025

ABSTRACT: Water, as vital natural resource, is indispensable for human activities, both directly and indirectly. It significantly contributes to a country's economic development, encompassing above-ground and underground water resources. However, ongoing pollution from surface contaminants is causing concerning degradation in both confined and unconfined aquifers, warranting the need for addressing this issue. Water quality indices (WQIs) serve this purpose by simplifying complex water quality data, providing a single value for easier interpretation. Surface water quality indices have achieved global recognition, while the development of groundwater quality indices is an evolving field. WQIs are established based on specific water quality criteria set by national and international organizations, which consider various parameters based on the intended use of water bodies. Consequently, numerous WQI models exist, including National Sanitation Foundation (NSFWQI), Oregon (OWQI), British Columbia (BCWQI), Canadian Council of Ministers of the Environments (CCMEWQI), and country-specific variants tailored to the unique requirements of individual regions such as Vietnam, India, Indonesia, Spain, Canada, Malaysia, and others, all in accordance with the specific characteristics of the water system under assessment.

Keywords: Water quality index; Water quality parameters; Physicochemical parameters; Microbiological parameters; Sub-index; Aggregation function

1. Introduction

Water is an essential resource for human and industrial progress, holding a prominent and exceedingly responsive role in the environment [1]. After the growing utilization of water resources, there has been a progressively rising demand and the identification of alterations in water quality conditions over time [2–5]. Due to rapid urban expansion driven by continuous economic and population growth, urban hydrological systems are constantly undergoing changes, leading to significant concerns regarding water quality (microbiological contamination and chemical pollution) [6–9].

Because of the insufficiency of surface water resources, the population predominately depends on groundwater resources, including a significant number of private wells such as drinking water, domestic use, industrial activities and irrigation [10–13].

The adverse effects of urbanization impact on water sources and natural flow patterns, along with potential modifications, create a range of environmental hazards that may ultimately impact human well-being. Additionally, these factors include disruptions in water balances, landscape transformations, and changes in rainfall patterns, contributing to the phenomenon known as "urban disease" [9,14,15]. Deterioration of surface water quality resulting from both natural processes and human activities makes it inappropriate for various purposes including drinking, industrial, agricultural, and recreational uses purposes. To deal with these changes and fluctuations in water chemistry, monitoring programs are essential for a reliable evaluation of surface water quality [16–19]. Evaluating water quality is a complex procedure including numerous parameters capable of exerting a significant impact on the overall water quality [20–24].

Several WQIs, such as NSF, CCME, BCWQI, ODEQ, and SRDD (Scottish Research Development Department), differ in their structure, parameters, weights, and sub-indexing methods [17,21,25–31]. Various WQIs have been tailored, yet they can often be applied elsewhere with or without adjustments. However, they may still carry some degree of inherent uncertainty [27,31–33].

https://doi.org/10.70322/hee.2025.10003

Prioritizing the global monitoring of water quality is a key aspect of resource conservation policy, with developing countries making an increased commitment to evaluating the quality of their rivers and lakes [22,31,34–36]. WQI, based on standardized parameters, is a universally accepted and dependable criterion for categorizing surface waters [37–43]. This review article summarizes various WQIs used to evaluate water quality, considering different parameters on specific water systems. The main goal is to compare these WQIs and engage in a critical discussion.

1.1. Historical Approach

The concept of evaluating water quality and classifying it based on cleanliness or pollution levels historically dates to 1848 in Germany [44]. In 1854, Snow made an innovative connection between poor water quality and the spread of cholera [45]. Much later, in 1965, Horton introduced the WQI to evaluate the quality of surface water [46]. Figure 1 and Table 1 present a historical overview of WQI development following Horton's model.

Figure 1. Historical/Geographic approach development of WQI.

Table 1. Historical approach development of WQI.

Development Year	WQI	Developing Country	WQI Use	Use in Other Countries	References
1970	NSF	USA	Popular/widely used for surface water		[47,48]
1971	SRDD	Scotland	river basins in different countries worldwide	Iran, Portugal, Romania, Spain, Thailand	[35,42,49–52]
1972	Dinious	USA	NSF modified version		[53]
1974	MWQI	Malaysia	surface water		[54,55]
1977	Ross	UK	only 4 parameters		[56]
1979	Bascaron	Spain	26 parameters	Argentina, Chile, Brazil, India, Turkey	[5,31,57]
1980	ODEQ	USA	surface water	improved Cude index (1970)	[43]
1983	Bhargava	India	river pollution		[58]
1986	House	UK	refined version of NSF		[59]
1989	Ganga by Ved Prakash et al.	India	River water		[60]
1990	Smith	New Zealand	protection of aquatic life		[61]
1992	ATI	South Africa	aquatic ecosystems		[62–64]
1993	Dojildo	Poland	river water		[65]
1995	BCWQI	Canada	aquatic life protection		[66]
1998	CI	Finland, Slovakia	Groundwater contamination		[67]
1999	Dalmatian	Croatia	drinking water		[68]

			use	
2001	CCMEWQI	Canada	simplified BCWQI	[69]
2002	OIP	India	surface water status	[70]
2004	Liou	Taiwan	river water quality (agricultural discharge, industrial/urban pollutants	[41]
2004	Said	USA	Simple/fast small number of parameters	[71]
2010	Hanh	Vietnam	spatial and temporal variations in surface water quality/pollution evaluation	[72]
2012	Almeida	Argentina	recreational water	[73]
2017	West Java	Indonesia	river water	[74]

1.2. WQI Development Process

The spread and evolution of WQIs were rapid, as they simplify water quality data for public understanding, providing information about overall quality and potential uses like irrigation, recreation, and consumption. Essentially, WQIs are straightforward tools for assessing water quality [75,76].

WQI development usually involves four steps: parameter selection, subindex calculation (transforming parameters to a common scale), assigning weighting coefficients to parameters, and aggregating subindices for a final score [60]. Parameter selection for WQI is guided by prior study results and potential harm to human health and the environment. Harmful parameters to human health are given higher weighting coefficients in the index calculation [41,71,77,78].

WQIs can be categorized into four main groups. The first consists of general-purpose indices applicable to various water types, with NSFWQI being a widely used example. The second contains more specific indices customized to different water uses like water networks or irrigation, such as OWQI and BCWQI. The third focuses on the development and design of quality indices, particularly relevant for water quality management and monitoring programs. The final group includes statistical indices analyzed using various statistical methods, excluding subjective approaches [27,79,80].

2. Water Quality Indices

Over the years a variety of WQIs were developed, using different water quality parameters, as each WQI was developed either for a specific water resource type or to simplify water quality assessment. This section includes a short presentation of each WQI.

2.1. Horton

The Horton WQI was the first one developed, which included as parameters dissolved oxygen (DO), pH, fecal coliforms (FC), *Escherichia coli* (*E. coli*), electroconductivity (EC), total dissolved solids (TDS), alkalinity, Cl-, chloroform extract (CCE), temperature, and apparent pollution (color, odor, oil, foam) [27]. Horton utilized a linear scaling function, assigning sub-index values on a 0–100 scale to represent concentration or contamination levels, with 0 as the lowest quality and 100 indicating excellence [81]:

$$\mathrm{WQI} = \left[\frac{W_1\ S_1 + W_2\,S_2 + W_3\ S_3 + \cdots + W_n\ S_n}{W_1\ + W_2\ + W_3\ + \cdots + W_n}\right] m_1\, m_2 \tag{1}$$

The WQI rating scale includes five categories: Very good (91–100), good (71–90), poor (51–70), bad (31–50), and very bad (0–30). Temperature contributes to determining the coefficients m_1 and m_2, with m_1 taking the value 0.5 when the temperature is above 34 °C and 1.0 when it's below 34 °C [46,82].

2.2. NSF

NSFWQI, based on the Delphi technique, assesses surface water quality utilizing nine parameters: BOD, DO, NO_3-, total phosphate (TP), Temp., turbidity (TU), total solids (TS), pH, and FC [82]. As time progresses, some parameters were substituted due to environmental issues, such as TS replaced by TDS or total suspended solids (TSS), TP by PO_4-P, and FC by *E. coli* [83].

NSFWQI value is calculated using weighting factors, rating curves, and water quality factors through the following equations (Equations (2)–(4)) [84,85]:

$$\text{NSFWQI} = \sum_{i=1}^{n} W_i Q_i \tag{2}$$

$$I = \sum_{i=1}^{n} I_i W_i \tag{3}$$

$$\sum_{i=1}^{n} W_i = 1 \tag{4}$$

where, I_i = each parameter indicator, W_i = weighting factor, Q_i = parameter evaluation value, i and n = number of individual indicators

NSFWQI classifies water quality into five categories: excellent (90–100), good (70–89), medium (50–69), bad (25–49), very bad quality (0–24) [85,86].

2.3. SRDD

The extensive utilization of the SRDD index in temperate and tropical-subtropical regions is attributed to its flexibility and regional applicability. It depends on eleven water quality parameters, chosen using the Delphi technique, grouped into four categories: physical (Temperature, conductivity, SS), chemical (DO, pH, NH_3-N and sal NH_3), organic (total oxide, N, P), and microbiological (BOD, EC) [49,51,52]. The SRDD equation is used for its calculation:

$$\text{RDD} - \text{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} S_i W_i\right)^2 \tag{5}$$

where S_iW_i = sum of the products of the water quality ratings and W_i = weighting of each individual parameter. SRDD classification: clean (90–100), good (80–89), good with treatment (70–79), tolerable (40–69), polluted (30–39), several polluted (20–29), piggery waste (0–19) [27,49–52,87].

2.4. Dinius

The multiplicative WQI, progressed through the Delphi technique, can be used in six water use categories (public supply, recreational, fish and shellfish, agriculture, and industry). It includes twelve parameters, including DO, BOD, *E. coli* and coliform concentration, pH, alkalinity, hardness, chlorides (Cl^-), specific conductivity (S.Cond), Temperature, color, and NO_x- [53,88,89]. Dinius WQI index value is determined using this equation:

$$\text{WQI} = \sum_{i=1}^{n} {I_i}^{W_i} \tag{6}$$

where I_i = pollutant parameter subindex function, W_i = unit weight pollutant parameter (ranging from 0 to 1), and n = number of pollutant parameters [53,88,89].

2.5. Malaysian

The index is calculated based on six standard physicochemical parameters: pH, DO, BOD, COD, NH_3-N, and SS. These parameters are chosen by experts, and for each parameter, a quality function (sub-index) can be determined [55,90,91]. The sub-indices are then combined to calculate the WQI using a specific equation:

$$\text{WQI} = 0.22^{*}SI_{DO} + 0.19^{*}SI_{BOD} + 0.16^{*}SI_{COD} + 0.15^{*}SI_{AN} + 0.16^{*}SI_{SS} + 0.12^{*}SI_{pH} \tag{7}$$

where SI_{DO} = DO (% saturation), SI_{BOD} = BOD, SI_{COD} = COD, SI_{AN} = NH_3-N, SI_{SS} = SS and SI_{pH} = pH.

MWQI (2020) classifies surface water quality into three groups: Clean (81–100), slightly polluted (60–80), and polluted (0–59) [54,90,91].

2.6. Ross

The WQI is determined using four parameters: BOD_5, NH_3-N, SS and DO. These parameters were selected based on prior research and using the Delphi technique. The equation used for calculating this index is as follows:

$$\mathrm{WQI} = \frac{\sum P_i}{\sum W_i} \tag{8}$$

where P_i = degree of each parameter and W_i = weight of each parameter.

Ross WQI categorizes river water quality into eleven levels, with higher values indicating better quality and lower values indicating poorer quality, including light pollution, moderate pollution, severe pollution, and poor quality [17,56,92].

2.7. Bascaron

BWQI includes 26 parameters for its calculation, including pH, BOD_5, Temp., TC, color, Turb., permanganate reduction, detergents, hardness, DO, pesticides, oil and grease, SO_4-, NO_3-, CN-, Na, free CO_2, NH_3-N, Cl, Cond., Mg, P, NO_2-, Ca, and apparent aspect [49]. This modified index has found application in various countries, such as Argentina, Chile, Brazil, India, Spain, and Turkey [5,31,57]. The Ross WQI, initially encompassing 26 parameters, provides flexibility by permitting the removal or replacement of specific parameters to suit the specific attributes of the water system under assessment [49,92,93]. The comprehensive index is determined subjectively using the following equation:

$$\mathrm{BWQI} = \sum_{i=1}^{i=n} (C_i p_i)^2 / 100 \tag{9}$$

In the equation, n represents the total number of parameters, C_i is the value assigned to parameter i after normalization, and p_i indicates the relative weight assigned to every parameter. The relative weight ranges from 1 to 4, with 4 signifying the highest impact and 1 suggesting the least impact on water quality [31,94–96].

2.8. Oregon

OWQI is a broadly recognized, easy to use index designed for assessing water quality in recreational activities like fishing and swimming. It incorporates eight parameters selected using the Delphi method: Temp., DO, BOD, pH, NH_4, NO_3, TP, TS, and FC. Cube later improved the index for surface water quality classification in the region. Particularly, OWQI doesn't use weighting factors, making it a straightforward tool for water quality assessment [43,82,97].

In its initial form, the OWQI uses a weighted mean numerical function, as follows:

$$\mathrm{WQI} = \sum_{i=1}^{n} SI_i\, W_i \tag{10}$$

The improved version of OWQI adapts to variable changes into account by assigning the greatest weight to the parameter that has undergone the most significant change, ensuring its prominent effect on the index. This updated equation recognizes that different water quality variables may contribute differently to overall water quality in various locations and at different times. The equation for the improved OWQI is as follows:

$$\mathrm{WQI} = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{SI_i^2}}} \tag{11}$$

where n = number of subindices and SI_i = sub index i. Based on the calculated index values, the classification of water quality is as follows: excellent (90–100), good (85–89), fair (80–84), bad (60–79), very bad (below 60) [43,82].

2.9. Bhargava

Simplification methods, such as the Bhargava method, strive to make water quality assessment user-friendly. This method categorized parameters into four sets based on raw water data from the Yamuna River in Delhi, India [58]. Each group evaluates specific types of parameters. The simplified WQI is represented by the following equation:

$$\mathrm{WQI} = \left[\sum_{i=1}^{n} f_i(P_i)\right]^{1/n} * 1 \tag{12}$$

where $f_i(P_i)$ = sensitivity function for each parameter including the effect of the variable weight concentration associated with a specific activity and ranges from 0 to 1, n = number of parameters. The Bhargava index's categorization for various water uses is as follows: I (90 and above), II (65–89), III (35–64), IV (11–34), V (10 or lower). Permissible categories for water use include only Class I and Class II [58,62,98].

2.10. House

HWQI represents an improved version of the NSFWQI, assessing nine water quality parameters (DO, NH_4-N, BOD, SS, NO_x^-, Temp., Cl, and TC). The Delphi technique is used to determine the weights assigned to these parameters. The equation is calculated as follows:

$$\text{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} q_i\, w_i\right)^2 \tag{13}$$

where n = number of sub-indicators, $q_i = i$ value of the sub-indicator and $w_i = i$-weight value and $w_1 + w_2 + w_3 + \ldots + w_n = 1$.

House index classifies river water quality into categories based on index values: high (71–100), reasonable (51–70), polluted (31–50), badly polluted (10–30) [27,59,99–101].

2.11. Ganga

This WQI was created to evaluate the Ganga River's water quality in India. It uses a modified version of the NSFWQI standard and considers four crucial parameters: DO, BOD, pH, and FC. This index helps identify areas in need of anti-pollution measures and provides a comprehensive evaluation of water quality along the river (CPCB, 2000). The equation for determining the overall index is outlined below:

$$\text{WQI} = \sum_{i=1}^{P} W_i\, I_i \tag{14}$$

where, P = number of quality parameters, I_i = sub-index for the i-water quality parameter, W_i = weight associated with the i-parameter [60,102]. Based on the final values of the Ganga index, water quality is classified into the following categories: excellent (90 and above), permissible (65–89), marginally suitable (35–64), inadequate for use (11–34), totally unsuitable (10 or lower) [60,103].

2.12. Smith

SWQI evaluates the suitability of water for multiple uses, including swimming, water supply, fish spawning, and aquatic life protection. It emphasizes the protection of aquatic ecosystems by selecting the parameter with the lowest score for establishing the final index. The Delphi method was used to select parameters for various, ensuring a systematic and well-informed approach to water quality assessment and management [61,62,104,105].

Smith proposed an alternative method to overcome the potential limitation of a multiplicative WQI. This method employs the minimum operator for index aggregation, avoiding a single parameter with a low value from disproportionately reducing the overall index score [61]. The Smith index is expressed by the following equation:

$$\text{WQI} = Min(I_1, I_2, I_3, \ldots) \tag{15}$$

where I = sub-index of the ith parameter.

The simplicity of the Smith index's application, which relies on the addition or subtraction of determinants, makes it easy to use. However, this simplicity comes with a potential drawback, as a single low-value indicator can disproportionately impact the overall score [62,104,105].

2.13. ATI (Aquatic Toxicity)

ATI, developed for the evaluation of aquatic ecosystems, incorporates diverse indicators related to fish toxicity and toxic effects. These indicators encompass a wide range of water quality parameters, including physical factors such as pH, DO, and Turb., alongside chemical parameters such as NH_3-N, TDS, F, K, orthophosphates (PO_4), and hazardous metals like Zn, Mn, Cr, Cu, Pb, and Ni [63,106,107]. The index's formula is used to provide a comprehensive evaluation of the overall condition of the aquatic ecosystem:

$$I = \frac{1}{100} \cdot \left(\frac{1}{n} \sum_{i=1}^{n} q_i \right)^2 \quad (16)$$

where, I = final index score, q_i = quality of the i-parameter (a value between 0–100), n = number of determinants. Not used for the calculation of this index is the classical weighted sum system, as there is not enough valid information about the importance of one determining factor in relation to the other in different conditions prevailing in different regions and the inherent chemistry of the system [62,64].

2.14. Dojildo

This index distinguishes between basic parameters, consistently used, and additional parameters, applied only in specific circumstances. The primary parameters, identified as frequently evaluated and significantly impactful in assessing water quality, include BOD_5, SS, P, NH_4, DS, COD, and DO. Supplementary parameters are introduced into the index calculation when their unit indicators indicate poorer water quality compared to the basic parameters. These parameters include Fe, phenols, organic nitrogen, hardness, Mn, pH, SO_4^{2-}, Cl, COD, NO_3^-, Pb, Hg, Cu, Cr, Zn, Cd, Ni, and free CN^-. The quantity of parameters considered significantly impacts the resulting index value [27,65,82]. The aggregation formula for the Dojildo Index is expressed as:

$$\mathrm{WQI} = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{S_i^2}}} \quad (17)$$

where n = number of indices considered and S_i = unit index of parameter i. This calculation method was selected because the average assigns a high statistical value to the parameter exhibiting the least favorable value, considering all parameters. Additionally, averaging provides the advantage of eliminating the weight of the various parameters [27,65,82].

2.15. British Columbia

BCWQI includes three essential components: range (quantity of variables not achieving water quality goals), frequency (how often those goals are not reached), and amplitude (the extent of deviation from the goals). It provides a numerical value ranging from 0 (indicating poor water quality) to 100 (representing excellent water quality) to evaluate the overall water quality [17,108]. The equation used to calculate the final value of CCME is as follows:

$$\mathrm{WQI} = \sqrt{(\mathrm{F}_1)^2 + (\mathrm{F}_2)^2 + \left(\frac{\mathrm{F}_3}{3}\right)^2} / 1.453 \quad (18)$$

where F_1 (Scope) = percentage of variables that do not meet their targets at least once during the time under consideration (“failed variables”). F_2 (Frequency) = percentage of individual tests that do not meet the targets (“failed tests”). F_3 (Amplitude) = amount by which the failed test values do not meet their targets. The 1.732 divisor normalizes the resulting values to a range between 0 and 100, where 0 represents the “worst” water quality and 100 the “best” water quality [17,71,108,109].

2.16. CI (Groundwater Contamination)

CI was formulated for groundwater quality, following European Environment Agency guidelines and EPA permissible limits, summing factors that exceed these standards. The CI designation is derived from the Mexican standard NOM-127-SSA1-1994 [62,67] and evaluates and maps groundwater contamination by examining ion concentrations and chemical species that surpass maximum levels established for water quality suitable for human consumption. It is calculated as the sum of individual components that exceed the values set in this standard [62,67].

While WQIs for surface water quality use the most commonly used quality indicators (e.g., BOD, SS, nitrogen and FC), CI includes a greater number of parameters, which also include trace metals, due to the significance they have in groundwater quality and contamination. Finland has developed two groundwater contamination indicators, one focusing on evaluating health risks and including the parameters: F^-, NO_3^-, UO_2^{2-}, As, B, Ba, Cd, Cr, Ni, Pb, Rn, and Se, the other indicator assessing technical and aesthetic considerations: pH, $KMnO_4$ consumption, SO_4^{2-}, Cl^-, Ag, Al, Cu, Fe, Mn, Na, and Zn.

In contrast, Slovakia employs a singular groundwater contamination index, determined by the parameters: TDS, SO_4^{2-}, Cl^-, F^-, NO_3^-, NH_4^+, Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, Sb, Se, and Zn. The value of the index is calculated using the following equation:

$$\mathrm{Cd} = \sum_{i=1}^{n} C_{fi} \tag{19}$$

where

$$C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1 \tag{20}$$

C_{fi} represents the contamination factor for the *i*th component, C_{Ai} stands for the analytical value of the *i*th component, and C_{Ni} represents the permissible upper concentration of the *i*th component (with "*N*" indicating the normal value). Groundwater contamination severity is categorized on a three-point scale: low (<1), medium (1–3), and high (>3) [62,67].

2.17. Dalmatian

To calculate the DWQI, the evaluation of water quality for a particular water body is divided by the assessment meeting Croatia's national standards for first-class water. DWQI is calculated based on nine parameters: Temp., mineralization, corrosion coefficient K, DO, BOD, TN, protein nitrogen, TP and total coliform (TC) bacteria (MPN coli/100 mL). The final index is calculated by aggregating all these parameters to evaluate water quality in the examined water system [68]. The DWQI is calculated with the following equation:

$$\mathrm{WQI} = \frac{\mathrm{WQE}}{\mathrm{WQE_{MAC}}} \tag{21}$$

The water quality evaluation (WQE) is determined by summing individual quality evaluations (q_i) and assigning weights to these parameters to derive the overall quality evaluation (w_i). This method is an adapted form of the SRDD index and is expressed by the following equation:

$$\mathrm{WQE} = \sum_{i=1}^{n} q_i w_i \tag{22}$$

$$\sum_{i=1}^{n} q_i w_i = weighed\ sum \tag{23}$$

where q_i = water quality score of parameters i, w_i = weighting factor of parameter i and n = number of parameters [68,110].

2.18. CCME

It's a widely recognized surface water quality index for its flexibility in parameter selection. It uses four parameters, selected according to water system characteristics and expert evaluation. Significantly, it doesn't involve calculating parameter indicator as seen in other models [60,111,112].

CCMEWQI evaluates factors like sampling frequency, frequency of not meeting target values, and parameter deviations to assess water quality. It aids in organizing data across all parameters, functioning as evaluating multi-dimensional water quality data. This simplified WQI uses a pre-programmed equation to evaluate the present condition of a water system, making it user-friendly for authorities to monitor changes in water quality [69,111,113].

The index is calculated by applying the following equation and considering 3 factors F1 (range), F2 (frequency) and F3 (amplitude):

$$\mathrm{WQI} = 100 - \left[\frac{\sqrt{\mathrm{F}_1^2 + \mathrm{F}_2^2 + \mathrm{F}_3^2}}{1.732}\right] \tag{24}$$

The divisor 1.732 normalizes the WQI to a range from 0 to 100, with 0 indicating poor water quality and 100 indicating excellent quality. This factor is based on the maximum possible values of the three index factors (F_1, F_2, and F_3), each having a maximum of 100. Consequently, the maximum numerator value is 1.732. [46].

The three factors, F_1, F_2 and F_3 are defined as:

F_1: "range", is the percentage of total parameters that do not meet the specified targets. It is expressed as:

$$F_1 = \left[\frac{number\ of\ failed\ parametres}{total\ of\ parametres}\right] \times 100 \quad (25)$$

F_2: "frequency", is the percentage of individual test values that do not meet the target values (failed tests). It is expressed as:

$$F_2 = \left[\frac{number\ of\ failed\ tests}{total\ of\ tests}\right] \times 100 \quad (26)$$

F_3, or "amplitude," measures the deviation of test values from their targets. It is calculated using an asymptotic function that scales the normalized sum of the paths (*nse*) of the test values from the targets, resulting in a value between 0 and 100:

$$F_3 = \left[\frac{nse}{0.01(nse) + 0.01}\right] \quad (27)$$

If a test value falls below the objective value, the deviation for that test value is determined as:

$$excursion_i = \left[\frac{failed\ test\ value_i}{Objective_j}\right] - 1 \quad (28)$$

Conversely, if the test value surpasses the objective value, the excursion value is calculated as:

$$excursion_i = \left[\frac{Objective_j}{failed\ test\ value_i}\right] - 1 \quad (29)$$

vse is the collective deviation of individual test values from their targets, calculated as the sum of deviations from targets, divided by the total number of tests, including those that meet and don't meet their respective targets:

$$nse = \left[\frac{\sum_{i=1}^{n} excursion_j}{total\ number\ of\ test}\right] - 1 \quad (30)$$

Based on CCMEWQI values, water quality is classified as excellent (95–100), good (80–94), fair (65–79), borderline (45–64), and poor (0–44) [27,113,114].

2.19. OIP (Overall Index of Pollution)

OIP was developed by India's National Environmental Research Institute (NEERI) for the assessment of surface water quality. It includes the parameters: pH, Turb., DO, BOD, hardness, TDS, TC, As, and F- using data from Indian river measurements [115,116]. OIP is calculated as the average of all pollution indices (P_i) for an individual parameter and is shown in the equation:

$$\mathrm{OIP} = \frac{\Sigma_i P_i}{n}\ \mathrm{OIP} = \frac{\Sigma_i P_i}{n} \quad (31)$$

where P_i = pollution index for *i*th parameter $i = 1, 2, \ldots, n$ and n = number of parameters.

Water quality was graded as: excellent (0–1, Class C1), acceptable (1–2, Class C2), slightly polluted (2–4, Class C3), polluted (4–8, Class C4), heavily polluted (8–16, Class C5) according to Indian standards and/or other accepted guidelines (World Health Organization and European Community Standards) [70,115,117].

2.20. Liou

LWQI was developed to evaluate the quality of river water in Taiwan, considering agricultural, industrial, and urban pollutants. It provides a proficient grading system. The calculation involves measurements from environmental monitoring and rating curves. Major parameters such as organics, particles, and microorganisms are analyzed and correlated. The final index considers three parameters: pH, Temp., and toxic substances. Classifying parameters aids in avoiding overlap and ambiguity concerns [41,49]. The aggregation function was derived through mathematical processing of the data, shown below:

$$\mathrm{RSI} = C_{tem} C_{pH} C_{tox} \left[\left(\sum_{i=1}^{3} I_i W_i \right) \times \left(\sum_{j=1}^{2} I_j W_j \right) \times \left(\sum_{k=1}^{1} I_k \right) \right]^{1/3} \quad (32)$$

Sub-index values are assigned based on the parameters they represent. For 'organics' (DO, BOD_5, and NH_3-N), sub-indices I_1, I_2, and I_3 are used. 'Particulates' (SS and Turb.) is represented by sub-indices I_j. Fecal coliform under 'microorganisms' is denoted as I_k. The geometric mean is utilized for the extracted components. Scaling factors (C_{tem}, C_{pH}, and C_{tox}) are also included in the calculation [49].

2.21. Said

SWQI consists of only five parameters and doesn't require standardization or sub-indices. Its development consisted of two stages: evaluating the significance of parameters such as DO, TP, FC, Turb., and S.Cond.; and weight ranking tests, which gave DO the highest weight, followed by fecal coliform and total phosphorus, while turbidity and specific conductivity had the lowest influence on the index calculation [17,26,27,71] The aggregation function was obtained after mathematically processing the data, as shown below:

$$\mathrm{WQI} = \log \left[\frac{(DO)^{1.5}}{(3.8)^{TP} (Turb)^{0.15} (15)^{FCol/10000} + 0.14 (SC)^{0.5}} \right] \quad (33)$$

where *DO* is DO (% oxygen saturation); *Turb* is Turbidity (Nephelometric turbidity units [NTU]); *TP* is total phosphate (mg/L); *FCol* is fecal coliform (counts/100 mL); *SC* is specific conductivity in (S/cm at 25 °C).

SWQI ranges from 0 to 3, with 3 representing ideal water quality. Scores between 3 and 2 indicate acceptable quality, while values below 2 suggest marginal quality, requiring additional treatment. If one or two parameters decline, the index falls below 2, and when the majority of parameters deteriorate, it decreases to values below 1, signifying poor water quality [27,71].

2.22. Universal

UWQI is a simplified indicator that evaluates the overall suitability of surface water for human use. It selects parameters according to expert opinions and international water quality standards. Important parameters include Cd, CN-, Hg, Se, As, F-, NO_3^-, DO, BOD, P, pH, and TC. Microbiological parameters carry greater weight in the calculations due to their significant impact on public health when present in drinking water [92,118,119]. The aggregation function is expressed as follows:

$$\mathrm{UWQI} = \sum_{i=1}^{n} W_i \, I_i \quad (34)$$

where W_i = weight for parameter *I*, I_i = subscript for parameter *i*.

The classification of surface water for human consumption based on UWQI values is excellent (95–100), good (75–94), fair (50–74), marginal (25–49) and poor (0–24) [92,118].

2.23. Hanh

Two indicators in Vietnam: WQI_B and WQI_O. WQI_B evaluates spatial and temporal water quality, considering the parameters SS and DO. WQI_O focuses on toxic substances such as CN- and heavy metals [27,72,82]. Following the above, the concentration function suggested for the basic WQI (WQI_B) is as follows:

$$\mathrm{WQI_B} = \left[\frac{1}{5} \sum_{i=1}^{5} q_i \times \frac{1}{2} \sum_{j=1}^{2} q_{j \times q_k} \right]^{1/3} \quad (35)$$

where q_i is the index value of organic and nutrient components, q_j, the index value of the particle group and q_k, the index value of bacteria.

Both the basic and additional groups of parameters are subsequently utilized to calculate the overall WQI (WQI_O). Therefore, the following WQI_O aggregation formula is as follows:

$$\mathrm{WQI_o} = \left(\prod_{1}^{n} C_i \right)^{1/n} \left[\frac{1}{5} \sum_{i=1}^{5} q_i \times \frac{1}{2} \sum_{j=1}^{2} q_{j \times q_k} \right]^{1/3} \quad (36)$$

where C_i are the coefficients concerning the sub-indicators T_w (water temperature), pH and toxic substances, and n, the number of coefficients. Therefore, based on the WQI_B or WQI_O score water quality can be classified as follows: 91–100, excellent water quality; 76–90, good water quality; 51–75, fair; 26–50, marginal; and 1–25 is poor water quality [72].

2.24. Almeida

For AWQI, select parameters associated with swimming and health hazards. Careful selection mitigates issues from additional variables and addresses ambiguity. Use score curves to establish connections between swimming-related illnesses and the index [17,27,73,120]. The calculation of RWQI can be determined using the following equation:

$$\mathrm{RWQI} = \prod_{i=1}^{n} Q_i^{W_i} \tag{37}$$

where, Q_i is the rating value of parameter i, W_i, the weighting coefficients ($\Sigma W_i = 1$) and Wi the effect of each parameter on the total value of the index.

To calculate each of them, their individual weight must be considered, which is calculated using the following formula:

$$W_i = \frac{\frac{1}{a_i}}{\Sigma \frac{1}{a_i}} \tag{38}$$

where, W_i, the weighting coefficient ($\Sigma W_i = 1$) and W_i is the effect of each parameter on the total value of the index. RWQI values fluctuate with parameter weights (a_i coefficients 1 to 4). Multiply parameter values with sub-indices (Q_I W_i) to obtain value ranges from 0 to 100. Higher values indicate superior quality [27,62,73].

2.25. West Java

WJWQI evaluates river water quality in West Java using the non-equal geometric method chosen for its simplicity and accuracy. Parameters are selected based on expert opinions and assigned weights using the Analytic Hierarchy Process (AHP). Six categories encompass a total of thirteen parameters: physical, oxygen depletion, nutrients, organic, minerals, and microbiological. The WJWQI aids in precisely evaluating the overall river water quality in West Java [74,121,122]. The final index value is calculated using the following equation:

$$AI = \prod_{i=1}^{n} S_i^{\omega_i} \tag{39}$$

where AI is the aggregate index, n, the number of sub-indices, w_i, the weight and S_i the sub-indicator i. The weights (w_i) reflect the importance of each water quality parameter in the index. The WJWQI score classifies water quality into categories: excellent (90–100), good (75–90), fair (50–75), marginal (25–50), and bad (5–25).

WJWQI serves as an effective water quality index for West Java's rivers and is widely used to evaluate the overall river water quality [74].

3. Discussion

All WQIs developed over the years tried to provide an easy and quick methodology for water quality assessment, nevertheless, WQIs have certain advantages and limitations. Specifically, the most commonly used WQIs, such as Horton NSF, Dinius, Malaysian, Ross Bascaron and Oregon use common water quality parameters (e.g., DO, pH, BOD, TDS, alkalinity and the major ions) to assess water quality status, therefore, they exclude major pollutant (e.g., heavy metals) from their assessment. Thus, in many cases, they can't safely estimate water quality. Other WQIs (e.g., Bhargana, House, ATI, Dojido, BCWQI, UWQI, WJ) tried to overcome these limitations by adding more water quality parameters (e.g., heavy metals and specific pollutants) in their analysis or by using a set of parameters in order also to increase the water quality parameters used. Their main limitation was the lack of data availability for all the water quality parameters. More details about the use of WQI are provided in the following discussion.

While various WQIs have been developed over the years, only a few are used more frequently either due to their simplicity or to data availability. Specifically, from 2013 until now, the most frequently employed water quality assessment indices in the literature include CCMEWQI and NSFWQ [26,82,123,124] (Table 2).

There are no distinct guidelines for the selection of water quality parameters in the development of a WQI. Criteria like oxygen, eutrophication, health, physical and chemical factors, and dissolved constituents influence parameter selection. Common WQI models are listed in Table 2 over the last 59 years [27,82,92,98,125].

Study results provide data for water quality assessment and underscore variations among assessment methods [7,21,125]. The calculation of a WQI in a water system involves determining the sampling points, timeframe, variables, and objectives. It can be utilized at various stations such as those spread across a lake, with data collected for a minimum of one year [17,27,126]. Combined data from different years is possible, but it may result in a loss of variability. Water quality objectives set numerical concentrations to support and protect designated water uses (e.g., drinking water). Parameter selection should consider their significance, relevance to WQI objectives, and data availability [17,26,27,82,127], while the sampling points and frequency are also important [128].

WQIs such as CCMEWQIWQI and BCWQI are widely used for effective water quality assessment, as indicated in Table 2, due to their validity, even when parameter values are low [79,129,130]. The NSFWQI index is used for river waters and provides a more representative representation of river water quality [129,131,132]. In recent research in different countries, the NSFWQI index has been utilized to classify water quality [39,86,126]. Chemical analyses of water samples have resulted in the development of water quality indicators tailored to specific regions, enabling regular monitoring to safeguard public health by ensuring the delivery of safe and healthy water to residents [38,133,134].

The quantity of selected parameters on WQIs can differ. For instance, Ross, Ganga, Smith, and CCMEWQI incorporate only four parameters in their calculations, as shown in Table 2 [48,56,60,61,104,112]. Numerous indices involve the incorporation of ten or more parameters in their development, such as Horton, NSFWQI, SRDD, Dinius, Aquatic Toxicity, BCWQI, Liou, UWQI, Hanh, and West Java [41,49,52,53,62,72,74,112,118,135]. Certain indices encompass an even greater number of parameters, such as the Bascaron WQI with 26 parameters, the Dojildo WQI with 19 parameters, and CI Slovakia with 19 parameters [49,62,65,67].

The availability of data related to the examined water body, plays a crucial role in parameter selection for WQI development, with the Delphi technique often used for this particular objective [112,136]. Certain indices select parameters by considering the availability of monitoring data and comparison standards (e.g., CI, Hanh, West Java) [62,72,74,112]. Specific indicates select parameters based on their environmental significance (e.g., Said) and public health (e.g., Liou) (Table 2) [41,71].

Indicators featuring a limited number of parameters, e.g., [56,61] prioritize physical parameters such as SS, DO, and BOD, along with turbidity, temperature, and pH. Microbiological parameters, particularly FC, are frequently included as well. In contrast, the CCMEWQI index doesn't define fixed parameters and their selection depends on the characteristics of the examined water body [56,60,61,103]. The Bascaron index involves 26 parameters, such as pH, BOD_5, DO, temperature, TC, color, turbidity, permanganate reduction, detergents, hardness, DO, pesticides, oil and grease, SO_4, NO_3, cyanides, sodium, free CO_2, ammonia-N, Cl, conductivity, Mg, P, NO_2, and apparent aspect (Table 2) [5,31,49,57].

Table 2. WQI summary.

WQI	Num. of Param.	Param.	Selection Process	Sub-Indexing	Weights	Aggregation Method	Classification
Horton (1965)	10	DO, pH, FC, *E. coli*, EC, TDS alkalinity, Cl^-, CCE, Temp., apparent pollution	Data availability of significant parameters				
NSF (1970)	9	BOD, DO, NO_3^-, TP, Temp., TU, TS, pH, FC	Delphi	Parameters directly used as sub-indicates	Unequal weights	Addictive formula (first version) Multicave formula (second version)	1. Excellent (90–100) 2. Good (70–89) 3. Medium (50–69) 4. Bad (25–49) 5. Very bad (0–24)
SRDD (1971)	10	DO, BOD_5, NH_3-N, sal NH_3, pH, TO, TN, TP, SS, Temp., Cond., EC	Delphi	Parameters directly used as sub-indicates	Unequal weights Sum of weights: 1	Addictive mathematical function Multiplicative NSF formula	1. Clean (90–100) 2. Good (80–89) 3. Good with treatment (70–79) 4. Tolerable (40–69) 5. Polluted (30–39) 6. Several polluted (20–29) 7. Piggery waste (0–19)
Dinius (1972)	12	DO, BOD, *E. coli*, coliform concentration, pH, alkalinity, hardness, Cl^-, S. Cond., Temp., color, NO_x^-	Delphi	Parameters directly used as sub-indicates	Unequal weights Sum of weights: 10	Multiplicative function	1. Purification not required (90–100) 2. Minor purification required (80–90) 3. Treatment required (50–80) 4. Doubtful (40–50)
Malaysian (1974)	6	pH, DO, BOD, COD, NH_3-N, SS		Parameters directly used as sub-indicates	Unequal weights Sum of weights: 1	Simple addictive function	
Ross (1977)	4	BOD_5, NH_3-N, SS, DO	Delphi	Parameters directly used as sub-indicates -rating curves developed by expert's opinions	Unequal weights Expert based Sum of weights: 10	Additive	Not specified
Bascaron (1979)	26	pH, BOD_5, Temp., TC, color, Turb., permanganate reduction, detergents, hardness, DO, pesticides, oil, grease, SO_4^-, NO_3^-, CN^-, Na, free CO_2, NH_3-N, Cl, Cond., Mg, P, NO_2^-, Ca, apparent aspect		Parameters directly used as sub-indicates (linear transformation function)	Unequal and fixed technique (Sum: 54)	Modified additive	1. Excellent (90–100) 2. Good (70–90) 3. Medium (50–70) 4. Bad (25–50) 5. Very bad (0–25)
OWQI (1980)	8	Temp., DO, BOD, pH, NH_4NO_3, TP, TS, FC	Delphi	Parameters directly used as sub-indicates	Unequal weights with sum of weights equal to 1 (first version) Equal weights (second version)	Addictive (first version) Unweighted—harmonic mean of squares of sub-indices (second version)	1. Excellent (90–100) 2. Good (85–89) 3. Fair (80–84) 4. Poor (60–79) 5. Very poor (<60)
Bhargava (1983)		4 sets of parameters: coliform organisms, heavy metals, physical, organic-inorganic		Parameters in the same group are aggregated to obtain 4 different group sub-indices	Unequal weights Sum of weights is 1	Modified multiplicative	1. Permissible (90>) 2. Permissible (65–89) 3. Not permissible (35–64) 4. Not permissible (11–34) 5. Not permissible (10<)
House (1986)	9	DO, NH_4-N, BOD, SS, NO_x^-, Temp., Cl, TC	Delphi	Parameters directly used as sub-indicates	Unequal weights Sum of weights is 1	Additive (SRDD aggregation technique)	1. Hight quality (71–100) 2. Reasonable quality (51–70) 3. Moderate quality (31–50)

							4. Polluted (10–30)
Ganga Index (Ved Prakash et al.) (1989)	4	DO, BOD, pH, FC		Parameters directly used as sub-indicates	Unequal weights Sum of weights: 1	Additive	1. Excellent (90>) 2. Permissible (65–89) 3. Marginaly suitable (35–64) 4. Inadequate for use (11–34) 5. Totally unsuitable (10<)
Smith (1990)	4	SS, Turb., Temp., BOD_5, FC (fish spawning)	Delphi	Parameters directly used as sub-indicates -rating curves developed by expert's opinions	Unequal weights Sum of weights: 1	Minimum operator function	Not specified
	7	DO, SS, Turb., Temp., BOD_5, NH_3-N, FC (water supply)					
ATI (1992)	14	NH_3-N, TDS, F, K, PO_4, Zn, Mn, Cr, Cu, Pb, Ni					
Dojildo (1993)	7	asic parametres BOD_5, SS, P, NH_4, DS, COD, DO		Parameters directly used as sub-indicates	Equal weights	Square root of the harmonic mean	1. Very clean (75–100) 2. Clean (50–75) 3. Polluted (25–50) 4. Very polluted (0–25)
	19	Additional parameters Fe, phenols, organic nitrogen, hardness, Mn, pH, SO_4^{2-}, Cl, COD, NO_3^-, Pb, Hg, Cu, Cr, Zn, Cd, Ni, CN^-					
BCWQI (1995)	10 (at least)	Common parameters (at least)	Open choice system	Sub-index assign based on expert opinion	Unequal weights Expert based	Simple specific mathematical formula	1. Excellent (0–3) 2. Good (4–17) 3. Fair (18–43) 4. Borderline (44–59) 5. Poor (60–100)
CI Filand (1998)	12	F^-, NO_3^-, UO_2^{2-}, As, B, Ba, Cd, Cr, Ni, Pb, Rn, Se (health-risk)	Monitoring data availability and comparison standards	Parameters directly used as sub-indicates	No used		1. Low (<1) 2. Medium (1–3) 3. High (>3)
	11	pH, $KMnO_4$ cons., SO_4^{2-}, Cl^-, Ag, Al, Cu, Fe, Mn, Na, Zn. (Technical-aesthetic)					
CI Slovakia (1998)	19	TDS, SO_4^{2-}, Cl^-, F^-, NO_3^-, NH_4^+, Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, Sb, Se, Zn	Monitoring data availability and comparison standards	Parameters directly used as sub-indicates	No used		1. Low (<1) 2. Medium (1–3) 3. High (>3)
Dalmatian (1999)	9	Temp., mineralization, corrosion coefficient, K, DO, BOD, TN, protein nitrogen, TP, TC	Delphi	Parameters directly used as sub-indicates	Unequal weights Sum of weights: 100	Automatic index formulas (additives or multiplicative)	Not specified
CCME (2001)	4	without specifying	Delphi	No used	No used	Fixed mathematical functions	1. Excellent (95–100) 2. Good (84–94) 3. Fair (65–79) 4. Marginal (45–65) 5. Poor (0–44)
OIP (2002)	9	pH, Turb., DO, BOD, hardness, TDS, TC, As, F^-					1. Excellent (0–1) 2. Acceptable (1–2) 3. Slightly polluted (2–4) 4. Polluted (4–8) 5. Heavily polluted (8–16)
Liou (2004)	13	main parameters: pH, DO, BOD_5, NH_3-N, SS, Turb., FC, Temp., toxic parameters,pH	Environmental and health significance	Parameters value used as sub-indicates	Equal weights		Not specified
Said (2004)	5	DO, TP, FC, Turb., S.Cond.	Environmental significance	Parameters value used as sub-indicates	Equal weights	Simple mathematical function	1. Highest purity (3) 2. Marginal quality (<2) 3. Poor quality (<1)
UWQI (2009)	12	Cd, CN^-, Hg, Se, As, F^-, NO^{3-}, DO, BOD, P, pH, TC	Delphi	Rating curve based sub-indexing system	Unequal weights	Multiplicative function	1. Excellent (95–100) 2. Good (75–94) 3. Fair (50–74) 4. Marginal (25–49)

							5. Poor (0–24)
Hanh (2010)	10 (at least)	SS, Turb,, DO, COD, BOD_5, PO_4, NH_3-N, TC, Temp., toxicity, pH	Monitoring data availability	Rating curve based sub-indexing system and developed on Vietnamese WQ standards	Equal weights	Combination of additive and multiplicative means (basic WQ-overall WQ)	1. Excellent (91–100) 2. Good (76–90) 3. Fair (51–75) 4. Marginal (26–50) 5. Poor (<25)
Almeida (2012)	9	pH, COD, NO_3, PO_4, detergents, enterococci, TC, FC, *E. coli*	Delphi	Rating curve based sub-indexing system and recommended by experts	Unequal weights Sum of weights: 1	Multiplicative mathematical function	1. Excellent (91–100) 2. Good (81–90) 3. Medium (71–80) 4. Poor (<70)
WJ (2017)	13	Temp., SS, COD, DO, NO_2^-, TP, detergents, phenols, Cl^-, Zn, Pb, Hg, FC	Monitoring data availability and comparison standards	Straight forward mathematical function with guideline value for generating sub-indexing	AHP Fixed/unequal weight values Experts' opinion Sum of weights:1	Non equal geometric technique	1. Excellent (90–100) 2. Good (90–75) 3. Fair (75–50) 4. Marginal (50–25) 5. Poor (25–5)

Most indices use rating curves to directly convert parameters into sub-indices, often with unequal weights. However, certain indices, such as Dojildo, Liou, Said, and Hanh assign equal parameter weights, while others like CI and CCMEWQI do not consider parameter weights during their development (Table 2) [41,48,62,65,67,71,72].

WQIs have been used in several studies, depending on their characteristics and data availability. For example, WQI which includes NO_3 and other major anions and cations, as parameters, has been used for groundwater quality assessment, as they can depict nitrogen pollution [137–141]. WQIs including major cations and anions are also mainly used to assess surface water as water resource for potable use [142,143].

4. Conclusions

WQIs are widely applied globally to evaluate and monitor water quality, particularly in areas facing issues related to water scarcity. These indices are mathematical models developed by studying and analyzing specific parameters selected for their relevance to the water source, sampling time, and geographical location. They function as potent instruments for evaluating the quality of the investigated water system, identifying pollution sources, and safeguarding surface waters.

Various indices are used depending on the parameters relevant to each water system and the suitability of their results. The WQI, NSFWQI, CCMEWQI, and BCWQI are among the main indices used in the evaluation of water quality, as they use as quality parameters the most commonly measured ones. The WQI is commonly used to evaluate the quality of river and lake water. The CCMEWQI and BCWQI exhibit greater efficiency and validity when dealing with low parameter values. The NSFWQI provides a more comprehensive perspective of river water quality worldwide. Furthermore, NSFWQI, CCMEWQI, and BCWQI can also be used with weights, which is extremely important, as they can take into consideration the different significance of the used parameters. Moreover, CCMEWQI and NSFWQ have been reported as the most frequently employed water quality assessment indices in the literature [26,82,123,124].

Over time, several additional WQIs have emerged, including fuzzy waters, heavy metals, land use-related water, tropical pollution level indices, and specifically tailored to post-mining activities. Developing a universally accepted WQI has proven to be challenging due to the diverse parameters found in different aquatic ecosystems.

However, distinct adaptations of the UWQI have been formulated to cater to the specific needs of drinking water, agricultural and industrial water (DWQI), river and lake water (OIP), recreational water, groundwater (CI), and water intended for fishing (ATI). Research into water quality indices is crucial in regions facing water scarcity, pollution issues, and areas implementing proactive measures to prevent water contamination. WQIs developed can be adapted and applied in other water ecosystems within the same area or globally, customized to particular data and conditions.

Author Contributions

Conceptualization, C.S.A. and P.A.; Methodology, C.S.A. and P.A.; Investigation, P.A.; Data Curation, P.A.; Writing—Original Draft Preparation, P.A.; Writing—Review & Editing, C.S.A.; Supervision, C.S.A.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Funding

This research received no external funding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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