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Research Article

A Review on Chemometrics and Climate Change: Insights from Malaysia Case Study

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Abstract

Climate change consider as main issues and concerns in Malaysia over the decade. Chemometrics techniques have been used in many climate change issues to address the limitations of climate change monitoring studies. In climate change areas, chemometrics is a valuable tool for assessing the correlation between different climate change factors, especially in vast and intricate databases. The purpose of the review was to evaluate and summarise the available data and restrictions regarding the use of chemometrics techniques in Malaysian environmental studies. The study conducted a thorough analysis of pertinent scientific papers published between 2019 to 2023 that addressed the main challenges related to climate change in the nation. The reviewed process including 25 publications with a climate change theme. The research that is now available indicates that chemometrics techniques are more accurate, flexible, and efficient when used in climate change modelling. Chemometrics are recently discovered in Malaysia's environmental area, thus future research should take a variety of aspects into consideration as the present studies only addressed a significant environmental challenges. Generally, chemometrics techniques offer numerous benefits in resolving climate change issues. The advancement of chemometrics in environmental research is imperative in Malaysia in order to produce greater contributions towards the efficient management of the environment.

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Introduction

Climate change refers to the gradual alteration of temperatures, weather patterns, and other climatic conditions. In Malaysia, the effects of climate change and environmental deterioration are becoming more apparent. According to climate scientists, over 25% of Malaysia's population is expected to face displacement due to climate change by 2030 [1]. The impact of climate change has grown more widely known throughout time as a result of regular news reports on extreme weather events, such as glacier melting and worldwide heatwaves [2].

Decennary, there has been an increasing awareness of the challenges related to climate change in Malaysia. As a result, numerous research on the subject have been conducted, and the chemometrics technique has been employed to address the limitations of these studies. In addition, chemometrics techniques have been crucial in helping to resolve problems in the environmental domain by applying statistical and analytical techniques, such as analysing water quality index (WQI) of a large region, researching various pollution indices of a specific area, analysing periodic data, and identifying different sources of pollution [3].

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The branch of environmental analytical chemistry called "chemometrics" uses multivariate statistical modelling and data processing. The chemometric techniques that are most frequently used in environmental investigations include artificial neural networks (ANN), discriminant analysis (DA), principal components analysis (PCA), factor analysis (FA), multiple linear regression (MLR), and hierarchical agglomerative cluster analysis (HACA or CA) [4]. Chemometrics has been used in a variety of environmental monitoring contexts, such as air quality, pollution, flood patterns, changes in land use, sedimentation, and erosion. Chemometrics analysis can be used to precisely, efficiently, and adaptably monitor environmental pollutants, optimise agricultural practices, enhance renewable energy systems, and improve climate modelling and prediction, among other applications that can help address climate change challenges [5].

Scientists and policy-makers could fully comprehend the intricacies of climate systems, spot trends and patterns, and make data-driven choices to abate global warming and prepare for its effects by utilising chemometrics approaches in climate change research. This study aimed to discover the application of chemometrics techniques for solving the climate change issue in relation to the sustainable development goals (SDG), specifically goals 13 on topic climate action and goals 11 on sustainable cities and communities. This paper describes the methods and major findings of the research project, which consists of three main components: climate change issues on, air pollution, water pollution and flood. Chemometrics application has multiple beneficial outcomes that could assist the country manage climate change more successfully.

Materials and method

This review was utilised carried out on the computer-based electronic search, a systematic and comprehensive search of the literature procedure to obtain all publications published between 2019 and 2023 that dealt with the application of chemometric technique in Malaysia. The initial stage of these research was utilizing and gathering databases from reputable, highly influential scientific papers online utilising search engines like Scopus, Web of Science, PubMed, Google Scholar and Research gate with the following research terms; *chemometrics, climate change, air pollution, heat waves, water pollution, water quality, ocean acidification, flood.*

The study covered all primary studies, regardless of design, published between 2019 and 2023 that examined the evaluation and analysis of Malaysia's climate change challenges using any chemometrics approach. Selecting literature from 2019 to 2023 ensuring the evaluation based on most recent scientific advancements, taking consideration on the most recent data and policy context as well as consists high-impact research that presently influencing the chemometrics field in monitoring environmental issues. This selection guarantees an in-depth and authoritative discussion of the subject, drawing on a broad spectrum of excellent, peer-reviewed literature to present an in-depth investigation of the relationship between chemometrics and climate change. A total of 50 studies were successfully collected, including both review papers and research article that were sources from high impact journals and reputable databases likely Web of Science, Google Scholar and Scopus. To improve the review's credibility, the papers were first evaluated by abstract before moving on to a final evaluation after duplicates were eliminated. A total of 25 studies were chosen for a thorough review. The inclusion and exclusion criteria listed below served as the foundation for the review's final evaluation.

The criteria for inclusion includes; (1) climate change studies set in Malaysia, (2) original research outlining the application of chemometrics, (3) all research designs, (4) publication between 2019 to 2023, (5) all in the language of English. Meanwhile, the exclusion criteria; (1) no citations were found for any of the research; and (2) reviews, commentary, and editorials. The overview on research approach is displayed in Figure 1 below.

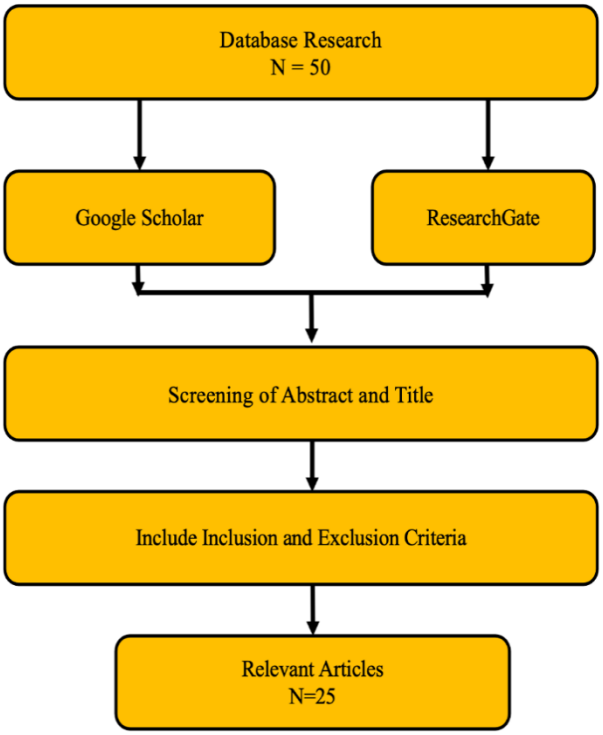

Figure 1 The overview on research strategy.

Results

The purpose of the evaluation process for the chosen publications was to demonstrate how chemometrics applications have evolved while remaining representative

of the various data sets. The categorization of various chemometrics methods used in the research examined in this paper according to the various data structures and study objectives are illustrated in Figure 2. Tables 1, 2, and 3 summarise the main environmental challenges in Malaysia that were the subject of 25 selected papers. The issues were (1) water pollution (n = 10), (2) air pollution (n = 10), and (3) floods (n = 5).

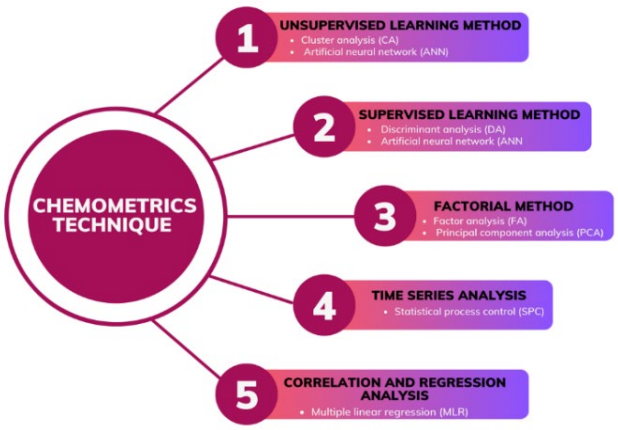

Figure 2 Classification of chemometric techniques.

1) Water pollution

The distribution, composition, and dynamics of pollutants in water bodies can be greatly impacted by changes in precipitation patterns, temperature swings, and extreme weather events from climate change [6] highlight the chemometrics techniques, in particular PCA-FA were significant to identify the river pollution. The research outcomes from river basin were similar to [7–9].

Table 1 indicated the chemometric study applied on the parameters and identification the source of pollution from Terengganu River basin [8]. The objective of the study was to identify the primary source of water contamination by using multivariate analysis to data on water quality collected from 13 monitoring stations within the study area. According to the study, chemometric techniques can provide valuable insights into the spatial variability of big and complicated river water quality data, which can help local authorities efficiently control pollution sources and provide helpful information for future research.

A case study conducted for rainwater harvesting [10] to determine the purity index on rainfall, focused on the assessment of multivariate statistical techniques that shown the effectiveness in assessing regional variations in water quality. Rainwater harvesting is a useful substitute technique that is primarily used for irrigation and non-potable domestic uses. Identical to study by Abdullah et al. [11], indicating that Peninsular Malaysia's rainwater was suitable for non-potable purpose such as irrigation, industrial processes, car washing, cooling system and many more.

Rising sea temperatures, shifting ocean currents, and extreme weather events linked to climate change all contribute to the spread and intensity of marine pollution. Research on marine water quality by Samsudin et al. [12] demonstrate that chemometrics technique on ANN was practical and efficient method for forecasting marine water quality index (MWQI) which consequently could analyze the trends in marine pollution. ANN are capable of learning complicated patterns in datasets that are not well-defined by straightforward mathematical formulas, as well as non-linear correlations between the variables [12].

Table 1 Application of chemometrics methods on water quality

No.	Chemometric techniques	Purpose of research	Findings	References
1	PCA, FA	Investigated the distribution of pollutants in three major river basins in Selangor.	This might be succeeded by adopting sustainable agricultural practices and imposing a more stringent standard for sewage and industrial effluent discharge .	[6]
2	PCA, ANN	Identify the significant parameters and potential sources of pollution that cause spatial variations along the Terengganu River Basin for 13 water quality monitoring stations upstream to downstream.	These findings proved the applicability of the PCA and ANN approaches as instruments for problem-solving and decision-making for improved river quality management.	[8]
3	CA	Assessment of Temenggor forest reserve water quality using physicochemical information and elemental content.	CA was able to evaluate the spatial variability among the sampling points by using the data set of elemental concentrations.	[15]

Table 1 Application of chemometrics methods on water quality (*continued*)

No.	Chemometric techniques	Purpose of research	Findings	References
4	PCA, HCA	Identifying the sources of water pollution improve Langat River basin management based on eight specific water intake points (from 2005–2015).	PCA for interpreting the sources of pollution and the contribution of each water quality indicator to identify the sources of pollution.	[7]
5	PCA, CA, HACA, DA	Evaluation of the water quality of Danau Kota Lake (from 2016–2017).	According to PCA, the organic pollutants in wastewater and industrial pollutants, along with the large amount of suspended algae, could be the sources of pollution in this lake.	[15]
6	ANN	Comparing prediction models for the marine water quality index in mangrove estuarine zones using spatial discriminant analysis (from 2011–2015).	ANN is a useful effective alternative method for forecasting MWQI in mangrove and estuarine zones. It can also be used in other contexts to analyse trends in marine pollution.	[12]
7	PCA, CA, DA	Assessment of the spatial water quality of certain chosen river basins across the three states of Malaysia.	Demonstrate the capacity of environmetric techniques to carry out the analysis and interpretation of a sizable, complicated data set for the purpose of assessing the quality of the water and identifying the sources of pollution.	[9]
8	PCA, DA, HACA	Determine the rainfall index's purity and, consequently, the dimensionality of the rainwater data in order to assess the quality of the rainwater (from 2017–2019).	Multivariate statistical techniques appear to have been effective in assessing regional variations in water quality.	[10]
9	PCA, DA, HACA	Analyze the characteristics and physicochemical properties of rainfall in Peninsular Malaysia (from 2017–2019).	Shown that Peninsular Malaysia's rainwater was suitable for non-potable purposes.	[11]
10	HCA, PCA, MLR	Assess the water quality dataset from lakes in Malacca and former mining ponds.	The results of multiplex investigations indicated that major variations in the water quality were caused by the disintegration of underlying rocks and current anthropogenic inputs.	[17]

Note: ANN = Artificial Neural Network; CA= cluster analysis; DA=discriminant analysis; HACA= hierarchical agglomerative cluster analysis; HCA=hierarchical agglomerative cluster; FA=factor analysis; MLR= multiple linear regression; PCA=principal components analysis; SPC=statistical process analysis.

Based on the table shown below, hierarchical cluster analysis (HCA) and DA were the dominant chemometrics techniques utilized in analysis water pollution. HCA assists researchers identify trends in the sources and locations of pollution by classifying similar water samples based on variables like pollutant concentrations [13], while DA aids in identifying the contaminants that are generating the contamination and classifying water samples into clean or polluted groups. Through the use of these chemometrics analysis, researchers can determine the source of contamination and implement preventative measures to maintain the safety and cleanliness of our water. Research from Jesi et al. [14] demonstrated the analysis of water quality using chemometrics, utilising HCA and PCA in the clustering and variables influencing the water quality and heavy metal concentration in the Klang River ecosystem.

2) Air pollution

The Earth's climate and air quality are both impacted by human activities that cause climate change, such as burning fossil fuels, which also release air pollutants. Research from Azizan et al. [18] utilize the PCA techniques to forecast the amount of air pollution was carried out in north region of Malaysia. The PCA, one of the chemometric approaches, was employed to minimise dimensionality by providing an overview of the information contained in large data tables. Moreover, the potential causes of variations in air quality were found using PCA.

A study by Ab Malek et al. [19] was conducted in southern peninsular Malaysia focused on modelling spatial air quality utilising chemometrics methods PCA. The primary objectives is discovering the major pollutants that significantly affected the research area's air quality. Southern Peninsula of Malaysia is bordered by

developing regions, the region's rapid industrialization and urbanisation are the primary causes of air pollution, thus leading to climate change.

In addition, Hua et al. [20] highlight the chemometrics techniques, in particular combination of chemometric techniques ANN with the principal component regression (PCR) were improving the prediction accuracy of air pollutant index (API). Study from Yusofa et al. [21] justify the ANN-SA technique proved to be highly feasible for forecasting future haze conditions in Malaysia. Similarly, Rahman et al. [22] proposed that the hybrid model created provides a forecasting approach for air quality and is precise enough to be used as a management tool for air quality.

Exposure to pollutants such as ozone and particulate matter can cause respiratory and cardiovascular diseases, thus indicating the air quality pollution and human health is profound. As mentioned by Mohd Isa et al. [23], multivariate statistical techniques appear to have been efficient in investigating the relationship and identify patterns between the concentrations of indoor pollutants and biomarker expression. Transportation, traffic, and industrial emissions were the main sources of particulates in urban and suburban areas.

In the context of air pollution, ANN are powerful instruments to evaluate vast amounts of data about pollutant concentrations, weather patterns, emission sources, and other environmental factors [24]. ANN discover the complex connections between these variables and forecast future pollution levels by working with past data. The principal components of PCA are a new collection of uncorrelated variables created by transforming the original data. For instance, PCA could demonstrate relationships or correlations between particular contaminants and particular weather conditions [25] which help to understand the dynamics and sources of air pollution in developing the mitigation strategies.

Table 2 Application of chemometrics methods on air quality

No.	Chemometric techniques	Purpose of research	Findings	References
1	PCA	Characterizing the spatial air quality monitoring stations of 14 north region station for two years (2018–2019).	The hybrid cluster analysis method employed in this investigation can yield more accurate pollutant distributions.	[18]
2	PCA	Determining the most dominant air pollutant in Southern Peninsular Malaysia by using Factor Analysis based on January - December 2018.	The major contribution sources to these pollutants are from induced emission of industrial activities and construction site.	[19]
3	PCA	Identify potential causes of air pollution in the Malaysian Federal Ports by analysing data (from 2009–2018).	PCA can be used to allow for variations among the primary possible sources of pollution and the types of sources of pollution.	[25]
4	ANN	Forecast the current status of the air quality and develop an API prediction based on 10 years data (from 2006–2015).	The study include ANN could increase the prediction accuracy of the API.	[20]
5	PCA-DA	Enhanced spatial cluster distribution with different validation and demonstrate the hybrid cluster approach in air quality monitoring stations in Peninsular Malaysia for two years (from 2018–2019).	Evaluation on the patterns of air monitoring are effective by hybrid clustering method.	[26]
6	PCA, AHC	Exploring the inflammatory phenotypes after exposure to indoor pollution (from 2018–2019).	Multivariate statistical techniques appear to have been effective in assessing air quality.	[23]
7	ANN	Forecasting $PM_{2.5}$ in Malaysia using a hybrid model.	The hybrid model created provides a forecasting approach for air quality and is precise enough to be used as a management tool for air quality.	[22]
8	ANN-SA	Determine the relationship of meteorological factors with air pollutant to PM_{10} variability (from 2006–2015).	ANN-SA technique proved to be highly feasible for forecasting future haze conditions in Malaysia.	[21]

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8	ANN-SA	Determine the relationship of meteorological factors with air pollutant to PM_{10} variability (from 2006–2015).	ANN-SA technique proved to be highly feasible for forecasting future haze conditions in Malaysia.	[21]
9	ANN	Assess the eastern region's pollutant-particulate matter (PM10) related status.	ANN outperformed the selected model and the entire model, with both models fully demonstrating a substantial outcome in both hazy and non-hazy.	[27]
10	ANN-SA, DA, HCA	Identify the primary pollutant causing issues with air quality and to track the spatial distribution of that primary pollutant throughout Peninsular Malaysia (from 2018–2019).	Justify the significant spatial variability for the assessment of large and complex air quality data.	[18]

Note: ANN = Artificial Neural Network; CA = cluster analysis; DA= discriminant analysis; HACA = hierarchical agglomerative cluster analysis; HCA= hierarchical agglomerative cluster; FA = factor analysis; MLR= multiple linear regression; PCA= principal components analysis; SPC = statistical process analysis

3) Flooding

Climate change contribute more intense and unpredictable precipitation patterns, sea level rise, and an increase in the frequency of extreme weather events, all of which increase the risk and severity of flooding in different parts of regions. Research by Jaafar et al. [28] concentrate on discovering the data variables and evaluating the risk of flooding at peninsular Malaysia. Table 3 shown the application of chemometrics techniques on flood.

Floods consider as natural disasters that could have catastrophic effects on more than two billion people worldwide [29]. Shafii et al. [30] described that the visualisation of flood patterns and the upper limit of flood management in the river basin were highlighted by the SPC analysis. Moreover, It was statistically demonstrated that the risk assessed by the ANN had a very high prediction performance accuracy of more than 99% [30]. Furthermore, flood risk assessment has been done at East Malaysia including Sabah and Sarawak [31–32]. Both of the research were applying

the chemometric techniques of PCA and SPC. These two techniques help in discovering the patterns and extract important data from complicated flood datasets, in order to better comprehend flood dynamics and develop efficient flood risk mitigation strategies [33]. It is concluded that chemometric approaches have proven to be an effective tool for flood mapping decision-making processes and for identifying the factors that contribute to flooding.

In addition, chemometrics demonstrated usefulness in risk assessment and predictive modelling. Study from Han and Wang [24], "Flood risk trend by using PCA and SPC analysis at Muda River, Kedah" focusing on data variables that lead to floods and evaluate the risk of flooding, such as the amount of rainfall. Meanwhile, research by Yusof et al. [27] "Flood risk pattern recognition in Kinabatangan River, Sabah utilizing PCA. Chemometrics approaches were utilised for both studies to analyse flood-related data with study of Han and Wang [24] that focused on SPC analysis can improve the Muda River Basin's flood warning system and research by Yusof et al. [27] which concentrated on decision-making procedures in flood mapping. These findings can be used to improve early warning systems and support infrastructure and urban planning initiatives. The effective use of GIS-based risk mapping and these prediction models in flood susceptibility mapping in Penang enhancing local disaster response and minimising flood damage [33].

Overall, the implementation of chemometrics in flood study provides an effective framework for comprehending the intricate relationships that exist between contaminants, water, and the environment [34]. Researchers and practitioners can obtain important insights into the origins, effects, and management of floods by utilising the analytical powers of chemometric methodologies. Hence, leads to the development of more effective flood risk mitigation and environmental conservation initiatives.

Table 3 Application of chemometrics methods on flooding

No.	Chemometric techniques	Purpose of research	Findings	References
1.	PCA, SPC	Determine the data variables that lead to floods and evaluate the risk of flooding in the Muda River basin, Kedah (from 2019–2021).	The result from the SPC analysis can improve the Muda River Basin's flood warning system.	[28]
2	PCA	Assess the regional variation of hydrological data in the Kinabatangan River, Sabah (from 1991–2019).	The integration of chemometrics techniques provided a powerful tool for decision-making procedures in flood mapping.	[31]
3	SPC, ANN, FA	Investigate the patterns of flood risk and the viability of using flow cytometry (FCM) as an assessment tool to comprehend the connection between flooding and waterborne illnesses in Malaysia.	The visualisation of flood patterns and the upper limit of flood management in the river basin were highlighted by the SPC analysis.	[30]
4	PCA, SPC	Evaluate the index of flood risk in the Rajang River Basin, Sarawak (from 1989–2019).	The application of SPC and PCA had identified the most important factors contributing to the occurrence of floods.	[32]
5	PCA, SPC	Identification and mitigation of flood risk.	PCA and SPC were used to identify data variables that trigger flooding and assess flood risk in the Muda River basin.	[34]

Note: ANN = Artificial Neural Network; CA = cluster analysis; DA = discriminant analysis; HACA = hierarchical agglomerative cluster analysis; HCA = hierarchical agglomerative cluster; FA = factor analysis; MLR = multiple linear regression; PCA = principal components analysis; SPC = statistical process analysis.

4) Research productivity globally

The total number of articles founds in Web of Science Core Collection (WOSCC) was 847 for all articles including "chemometrics" and environmental". Figure 3 shows the number of publications has been rising annually. The number of articles published in those topics were increased, indicating an upward trend in research activity from the past decade (2013–2023). During the rapid development stage of the research (2013–2018), the research topic continued to attract the interest of academic, as demonstrated by the rise in published publications and the expansion of research issues and perspectives. From (2018-present); the stable in-depth stage, the trend in literature publications was consistently increased with the perspective and content of the research deepened throughout time.

The global distribution for the number of published articles on field chemometrics and environmental were shown in Figure 4. The geographic distribution of the total amount of published papers from the WOSCC database were visualised by utilizing the website mapchart. The leading countries in this relevant topics were China with total publications of 261 articles. Moreover, Brazil ranked second with 83 result count for publications. USA, Spain and Italy were among the countries with 50–100 total publications. This research also showed that there were less of studies carried out in African and South America regions for this topic.

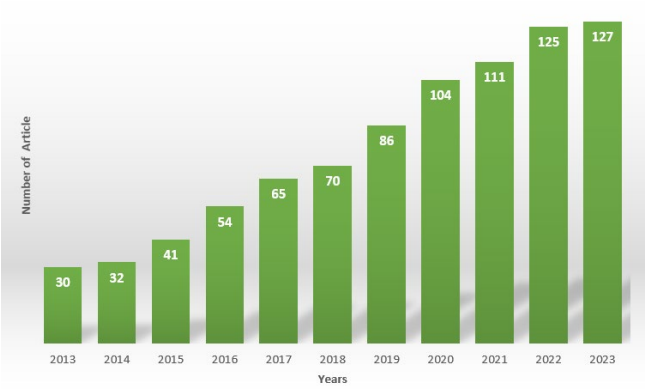

Figure 3 Publication trend on chemometrics and environmental annually (2013–2023).

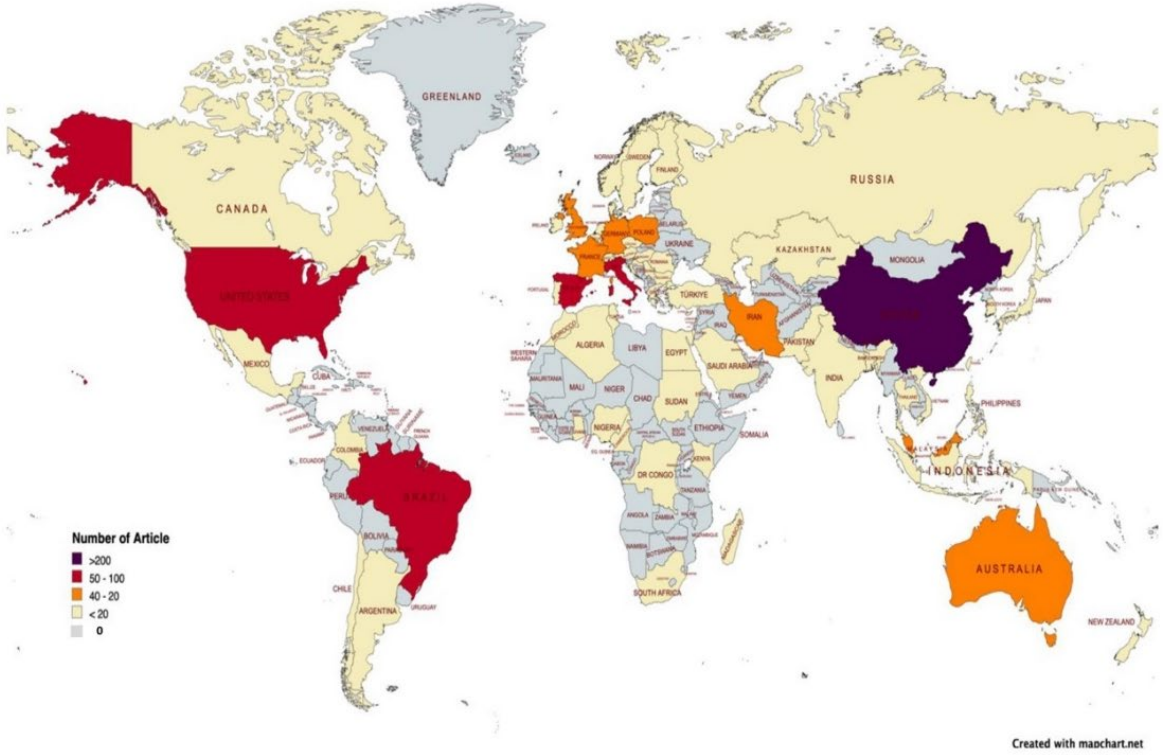

Figure 4 Global distribution for the number of published articles on chemometrics and environmental.
Source: website https://www.mapchart.net/world.html

Discussion

1) The role of chemometrics in climate change analysis

Chemometric methods were essential for understanding the complex processes of climate change and provide important information on the interaction of several aspects of the environment [5]. In order to analyse, evaluate, and extract useful information from complicated climate datasets, chemometrics offers useful techniques and approaches which helps gain insight into climate change and its effects on the environment and society [35] likely from examining greenhouse gas concentrations to investigate the chemical composition of aerosols and contaminants. Among the many disciplines that contribute to the research of climate change, chemometrics stands out as an effective set of tools with huge potential. Chemometrics plays a variety of roles in the research of climate change, from data interpretation and analysis to enhancing our knowledge of atmospheric processes and emission sources, thus improving the efforts in mitigate and adapt to the effects of climate change and leading the way for a sustainable future.

Additionally, chemometrics techniques enable the integration of diverse datasets from several sources, such as ground-based measurements, climate models, and satellite observations [36]. Researchers combining information from many sources to increase the precision of climate projections and enhance the comprehension of the dynamics of the climate system by using data fusion and multivariate analysis [37]. Additionally, chemometrics techniques (PCA, SPC, ANN and etc.) is

used in soil analysis, flood risk assessment, and water quality monitoring in climate change research. These skills are especially important in places like Malaysia, where public safety and environmental management are severely constrained by climate change. Future studies could investigate on improving environmental monitoring and management skills by integrating chemometrics with modern technology like artificial intelligence and the internet of things.

2) Climate change as competitiveness factor

As Malaysia continues to rapidly develop, the country's currently experiencing increment in levels of pollution, environmental degradation, and climate change issues. Climate change may be speeding up the processes endangering Malaysia's natural resources, according to concerns [38] which the Tenth and Eleventh National Plans of Malaysia (2011–2015 and 2016–2020, respectively) have allocated substantial funds towards enhancing adaptation to climate change. Although Malaysia continues to be one of the world's richest in biodiversity, the nation struggles with ecosystem deterioration in both its forest and wetland areas [39]. The effects of climate change on Malaysia's competitiveness are complex and affect several areas, such as worldwide perceptions of environmental responsibility, resource availability, market needs for sustainable products, and environmental regulations.

The SDGs, especially goal 12, concentrate on patterns of consumption and production which provide opportunities over the efficient use of resources, lessen the environmental footprint embarked by economic activity, minimise the environmental impact of economic activity, and increase economic competitiveness [40]. Moreover, climate change is causing stricter environmental regulations around the world, which is affecting the competitiveness of Malaysian industry [41]. On the economic verge, Zia et al. [42] reported that its projected that by 2020, the severe consequences of pests, diseases, war, and climate change will reduce food production, disrupt supply chains, and make it more challenging for people to get good food at reasonable or cheap costs, endangering the competitiveness of agricultural sector.

Another sector that affected were tourism and energy sector. Malaysia is currently facing weather instability that could result in wildfires, droughts, floods, and an increase in sea level [43] which consequently effects of climate change on tourism are significant because they raise the risk of animal extinction, deplete freshwater supplies, increase the likelihood of wildfires, heat waves, and illnesses, all of which discourage tourists from visiting particular areas [44]. Numerous recent studies have highlighted the economic growth potential of tourism, and it is anticipated that this sector will continue to be a major driver of growth and opportunity, especially in many smaller nations [45]. Thus, climate change could cause competitiveness in the tourism sector to deplete.

Renewable energy is an essential part of energy which simultaneously preserves the environment and optimises the current energy mix while balancing market contradictions [46]. A major factor in the global economy's shift to sustainable development is renewable energy, such as hydropower, wind, solar, and bioenergy [47]. At the same time, climate change also affects the sector's energy supply and demand, together with viability of economic thus influencing competitiveness [48].

Natural catastrophes, or occurrences brought on by natural processes like floods or landslides, can have disastrous effects and expose the vulnerability of people and property [49]. As stated by Alam et al. [50], Malaysia is among the nations in the Asia-Pacific area most prone to natural disasters such droughts, landslides, floods, and climate change. Managing climate change becomes essential for preserving and improving competitiveness in the global market as Malaysia and other nations navigate continued fast expansion and globalisation [51]. In order to reduce the risks associated with climate change, promote resilience, and ensure long-term economic development, proactive adaption measures, investments in sustainable technology, and cross-sector and cross-border collaboration are crucial [52].

3) The benefits of chemometric methods

Chemometrics is a comparatively new area within chemical science that seeks to extract as many quantitative details from chemical data as possible for use in various environmental pollution assessment contexts. It does this by modelling and optimising analytical and chemical processes and applying statistical, mathematical, and logic-based approaches to the assessment and interpretation of analytical and experimental data [53]. It has been observed that chemometrics greatly reduces the bulk data from environmental monitoring and assessment. Chemometric approaches are more dependable and advantageous to different authorities as it helps to minimise redundant parameters by increasing focus on important environmental elements [54].

Figure 5 illustrated the benefits of chemometrics techniques. The reduction or elimination of analytical mistakes is a primary goal when using chemometrics [55]. Shafii et al. [4] highlighted that using integrated chemometrics techniques also helps to better understand environmental issues brought on by pollution and effectively explain a complicated collection of chemical data from the environment.

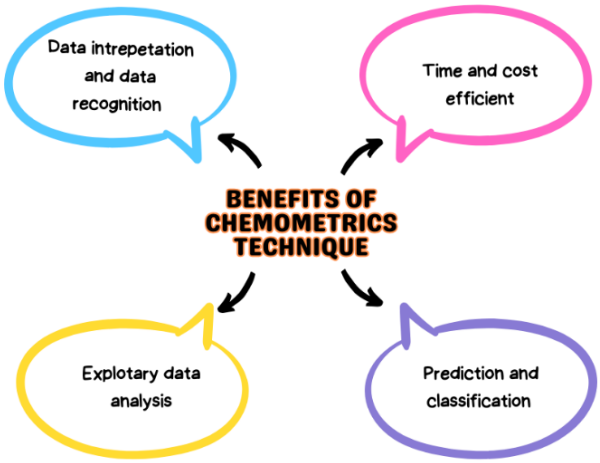

Figure 5 The benefits of chemometrics techniques.

For a comprehensive and more dependable understanding of the type and trend of pollution in various environmental components, researchers have used a variety of chemometric analysis techniques, including the most recent developments in artificial neural networks [56]. Chemometrics exhibits greater potential in the environment sector than traditional techniques because it can evaluate both quantitative and qualitative techniques present between environment variables [57]. Hence, chemometrics is a better method for monitoring and evaluating the environment since it helps the government and research organisations predict future pollution patterns [56].

Applying chemometrics to the study of climate change has an array of benefits and is important for comprehending and resolving the complexity of this worldwide problem. Primarily, chemometrics gives researchers sophisticated mathematical and statistical tools to examine large and complex datasets pertaining to climate variables like temperature, air composition, and greenhouse gas concentrations [24]. The linkage between chemometrics technology and climate change events stand between the ability to analyse, evaluate, and forecast climate data provides crucial insights into the effects of climate change and improves mitigation and adaptation initiatives. Thus, this analytical skill helps decision-makers prioritise adaptation and mitigation strategies, evaluate the efficacy of climate policies, and make well-informed decisions, ultimately paving the way for a future that is more resilient and sustainable in the face of climate change [53]. Chemometrics makes it possible for researchers to identify patterns, trends, and linkages in climate data using methods like multivariate analysis and receptor modelling, which improves our understanding of the dynamics of climate change [58].

4) Consequences towards climate change management in Malaysia

The three primary climate change issues in Malaysia that are addressed by the application of chemometric approaches are air quality, water quality, and flooding. For river and marine water quality and pollution, it was responsible by Malaysia Department of Environment (DOE) for monitoring. The National Water Quality Standards for Malaysia (NWQS) and the Water Quality Index (WQI) are used to assess the quality of river water [59]. To determine the level of water pollution, the WQI was developed using a sub-index of six primary parameters: pH, total suspended solids (TSS), dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and nitrogen ammonia (NH_3–N).

The Malaysian Department of Environment (DOE) tracks ambient air quality and reports its findings using the Malaysian Air Pollutant Index (API). Currently, there were 14 Manual Air Quality Monitoring (MAQM) and 52 Continuous Air Quality Monitoring (CAQM) stations nationwide [60]. Residential, industrial areas and traffic were chosen as the location for monitoring stations to identify any changes in the air quality that could bring harmful to environment and human health. The monitoring category includes particulate matter 10 micrometres in diameter (PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3), and a recently discovered pollutant, particulate matter 2.5 micrometres in diameter ($PM_{2.5}$) [60].

The Malaysian Department of Irrigation and Drainage (DID) has created a new National Flood Forecasting and Warning System (NaFFWS/RAB) with the goal of reducing the impact of hazard and disaster risks and providing accurate and reliable forecasts and warnings of approaching floods for public safety [61]. The Malaysian Meteorological Department's numerical weather prediction rainfall predictions, spatial rainfall radar data, and real-time, telemetered gauged data from DID's own Info Banjir database power the completely automated systems that comprise up the NaFFWS [4].

Future outlook and research opportunities

Chemometrics has a promising future filled with chances for multidisciplinary cooperation, ongoing research, and practical application in a range of industries [62]. All areas of life have made extensive use of contemporary spectral analysis techniques powered by chemometrics, particularly industrial on-line real-time analysis and on-site quick analysis [63]. Future-oriented sectors will depend more and more on data-driven optimisation and decision-making, and chemometrics will be crucial

to boosting productivity, sustainability, and competitiveness [64].

Stated by Chapman et al. [65], there are plenty of research opportunities in the field of chemometrics for addressing climate change challenges, providing pathways for creative solutions and significant contributions. For instance, the application of chemometrics in optimizing systems of renewable energy, enhancing carbon capture technology, enhance soil management and agricultural operations provides encouraging opportunities for future study on addressing climate change [66-67]. Scientists and researchers may employ chemometrics to address climate change concerns, promote innovation, and contribute to a more resilient and sustainable future by investigating these study opportunities [68].

Conclusions

The chemometrics techniques discovered various advantages for climate change, as well as the practicality and effectiveness tool for resolving environmental concerns in Malaysia. Nevertheless as this review has demonstrated, more advancements in chemometrics are required to improve knowledge and present more substantial implications for improved environmental management in the future, especially in Malaysia. It is anticipated that applying these chemometrics approach will strengthen and improve environmental monitoring on climate change issues and advantageously impact on research and government policy.

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