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*Research Article*

# Prioritising Actions for Improving Classroom Air Quality Based on the Analytic Hierarchy Process: Case Studies in China and the UK

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The air quality in classrooms significantly impacts school children's health and learning performance. It has been reported worldwide that classroom air quality does not meet the required standard and actions are pledged for improvement. However, it poses a challenge for decision-making in terms of prioritising taking-up measures. The aim of this study is to propose a method of identifying the action measures for improving classroom air quality and prioritising them. Case studies in the UK and China were conducted, and the key measures were identified through literature studies, open-ended questionnaire surveys, and workshop discussions, which are classified into three categories: B1, policy; B2, technology; and B3, information sharing. The analytical hierarchy process (AHP) is applied in the prioritisation of the action measures. A total of 138 teachers and parents from China and the UK participated in this case study. The genetic algorithm-optimised Hadamard product (GAOHP) method is applied to justify the consistency ratio (CR) within the required threshold value in order to ensure the consistency of the subjective perception and the accuracy of comparative weights. The results show that item B2, technology, is the most desired measure by both Chinese and British parents and teachers, despite the deviation from the optimal choice in China and the UK. Among the proposed action measures, the UK respondents strongly expected air purifiers with natural ventilation as opposed to their Chinese counterparts preferring to share the real-time status of classroom air quality. Our work will provide strong support for the subsequent selection of indoor air quality improvement strategies for schools.

## 1. Introduction

Children spend the majority of their days at school, making the environment within these institutions crucial to their overall well-being and learning capabilities. Yet, there has been growing concern over the conditions within schools. Research has consistently indicated that school conditions, particularly the classroom air quality (CAQ), are often less than ideal—sometimes even poorer than air quality in offices or homes [1, 2]. Such conditions not only compromise the comfort of students but have been directly linked to health issues [2–4], particularly given the vulnerability of children due to their developing physiology [5, 6]. Poor conditions in schools are also known to impact learning progression [7–9]. This may impact the children's future quality of life and have economic implications for society [10, 11]. Different countries, with distinct geographical, cultural, and infrastructural factors, face unique air quality challenges in their schools. The classroom air quality (CAQ) depends on the sources of pollution present indoors, the transmission of pollutants from outdoors, and the dilution and removal of pollutants achieved by ventilation. The type of ventilation system and air distribution within the classroom will also impact the quality of air. Recent research examining the effects of CAQ on children's cognitive performance and learning has addressed the factors that impact indoor air quality (IAQ) with emphasis on ventilation rates per person (l/s/person) as the indicator [12–14]. Research has shown that the level of $CO_2$ in classrooms can increase to very high values due to inadequate ventilation rates [15]. It is generally assumed that the higher the $CO_2$ concentration, the poorer the air quality will be. Wargocki et al. found that increasing ventilation in classrooms to 10 l/s/person would bring significant benefits by improving learning and reducing absenteeism [12]. In terms of $CO_2$, it was found that its concentration should be kept at or below 900 ppm. Although $CO_2$ has frequently been used to characterize air quality in classrooms, some research has focused on other specific pollutants such as particulate matter [8, 16, 17].

Source control is an important way to improve IAQ. Raysoni et al. [18] showed that the primary source of PM contamination in schools is outdoor air. Particles also enter schools via ventilation and infiltration from outside, especially in metropolitan areas where automobile exhausts are the primary source [19–21]. The school's location plays a significant role in formulating its indoor and direct outdoor air quality. $PM_{10}$ and total bacteria count levels for schools surrounded by roadways were found to be significantly lower than those surrounded by buildings and mountains [22]. Ventilation is usually used as a useful way to improve IAQ [23]. Studies show the benefits of using mechanical ventilation systems in schools [23, 24]. Usually, old schools without mechanical ventilation rely heavily on natural ventilation (natural driving forces), which requires careful management of opening windows to be effective [25]. Air filtration units (AFUs) are often used to reduce exposure to air pollution. The results of a study about the effectiveness of AFUs in classrooms in China showed that significant $PM_{2.5}$ reduction is found in classrooms equipped with AFU [26]. Air purifiers could also improve air quality. A study showed that air purifiers lighten the medication burden in children with asthma by reducing $PM_{2.5}$ levels [27]. Targeted implementation of green infrastructure (like trees, hedges, living walls, green roofs, and green screens) along busy roadsides can reduce air pollution exposure [28, 29]. IAQ monitoring devices can be an effective mechanism to promote people's engagement in improving IAQ when IAQ information is properly presented [30]. The provision of IAQ visualization would raise awareness about the effects of indoor activities on IAQ and thereby empower occupants to make a rational decision to steer habitual behaviours towards an environmentally sustainable direction [31].

Air quality in schools is currently a concern in both China and the UK. A recent study by Global Action Plan found that a quarter of children in the UK attend a school where air pollution is worse than the World Health Organization limit, with metropolises such as London, Manchester, and Leicester being among the worst polluted areas [32]. Schools in London have been shown to have much higher air pollution levels than any other area. Research has shown that 98% of state schools in London are in areas that exceed World Health Organization (WHO) pollution limits, compared with 24% outside London [33]. The IAQ of 66 classrooms of 22 primary schools nationwide in China was performed in a worldwide IAQ measurement. The results showed that there were 66.5%, 52.6%, 22.4%, 1.8%, and 9.6% of the classrooms exceeded the guideline values of $PM_{2.5}$, $PM_{10}$, $CO_2$, HCHO, and bacteria, respectively. Indoor air pollution in classrooms was a severe problem in Chinese primary schools [34].

Schools worldwide are taking action to improve air quality. Schools in the UK are taking measures to try to deter parents from using their cars. These include closing roads, setting up "park and stride" schemes, walk-to-school initiatives, and "playing dead" protests [35]. Other suggestions are taking their scooter or bike to school or using public transport. The research found support from London parents for safer crossings (57%), 20 mph speed limits (51%), car-free zones around schools (43%), and efforts to reduce rat-running (41%) [36]. Recent research [35] revealed that eight in ten parents (83%) are keen to change their school-run habits in order to improve air quality around their child's school and develop more sustainable communities. The central London Ultra Low Emission Zone (ULEZ) will ensure these tougher emission standards reduce $PM_{2.5}$ exhaust emissions by 35% in inner London [33]. Install air filtration units (AFUs) in classrooms are used as a common way to improve the indoor air of schools. Many Chinese cities such as Beijing and Xi'an have launched pilot projects to install AFUs in classrooms to reduce indoor air pollution [26]. Schools in different regions of China propose different methods to improve indoor air quality in response to local conditions [37, 38].

Clean air in schools benefits students and staff, both in terms of their physical health and learning capacity. Numerous epidemiological studies have linked poor air quality with reduced attendance rates at school [12, 39, 40]. Schools worldwide suffer from both poor local air quality [41, 42] and indoor pollutants. A wide range of effective actions can be taken to resolve this situation, including reducing vehicle movements around schools, improving ventilation, and prioritising purchasing equipment and furniture that do not emit harmful pollutants. However, each action varies in the potential for improving air quality, the money and time needed for implementation, the pollutants addressed, and its applicability to specific schools. While these actions underscore the commitment to enhancing CAQ, they also illuminate a crucial gap in the existing academic landscape: the lack of studies focusing on the prioritisation of these measures. With varying costs, policies, effectiveness, and stakeholder willingness associated with each intervention, there is an evident need for a methodical approach. It is therefore important to develop a method for prioritisation of measures for air quality improvement to derive the greatest benefits for health and learning from the financial and time resources that are available. By adopting a structured methodology like the analytic hierarchy process (AHP), we can systematically assess and rank the plethora of interventions. This process will not only gauge each measure's relative significance but also account for diverse factors such as cost, policy implications, and stakeholder preferences. The aim of this study is to provide guidance to policymakers and stakeholders in deploying their resources most effectively, ensuring that the measures adopted deliver the maximum benefit in improving CAQ. Absent such a systematic evaluation and prioritisation, the risk runs high of squandering both time and resources on less impactful measures, thereby diluting the potential for meaningful improvement in CAQ.

To achieve the overarching aim, the objectives were set up including (1) developing the methodology to identify the commonly expected action measures by engaging school users, (2) determining the most used measures for improving CAQ, and (3) prioritising the measures by school users using the AHP method. By addressing the intricate web of factors influencing CAQ and prioritising interventions, this study broadens IEQ assessments and strives to create healthier, more supportive learning environments worldwide.

## 2. Methods

*2.1. Framework for Identification and Ranking of the Measures to Improve IAQ.* This case study for prioritising the measures for improving classroom IAQ has been conducted in the following three main stages (see Figure 1). Stage one is to identify potential solutions for improving CAQ through an extensive review of the published literature and related documentation, the report from the workshop discussion organized by the Tackling Air Pollution at School (TAPAS project, https://tapasnetwork.co.uk/) school design and management guidelines, and open-ended questionnaire surveys. The second stage is to refine the list of potential measures derived from the first stage through a number of consultations with school teachers and parents as well as workshop discussions. The third stage is to define the urgency associated with each identified measure that is considered to be prioritised to implement. Measures of improving air quality can be assessed based on their performance considering a range of criteria with different weights/priorities. Objective and subjective weightings are two main approaches for the identification of priorities [43]. In this study, the measures and their associated categories are assessed subjectively to define their associated weights. This is because this approach takes into account the experience of decision-makers and the concerns of policymakers in the implication of weight in the successful delivery of the most appropriate measures. Analytical hierarchy process (AHP) is a multicriteria decision-making method combining qualitative and quantitative analyses mainly proposed by the famous American operations researcher T.L. Satyr in the 1920s [42]. It is adopted in this study because of its ability to provide a pairwise comparison between criteria and also its offer of consistency analysis [44]. The evaluation of consistency is a key element in the evaluation of subjective weights to ensure that there is no contradiction between the opinions offered by each participant, especially in cases with a broad range of measures available in different hierarchy levels. With more fair judgment, extreme individual preference influence can be avoided. The AHP method is recommended to be extended to verify and validate CAQ improvement.

*2.2. Stage 1—Identify and Cluster the Measure for Improving IAQ through an Extensive Review.* The scope of this extensive review is limited to potential measures that are related mainly to improving CAQ. By summarizing the related guidelines and program reports, keywords and phrases are identified as the following: mitigation measures, interventions, schools, classrooms, IAQ, green screens, air purifiers, ventilation, behaviour changes, monitors, and awareness raising [45–51]. These keywords were searched in the journal title, abstract, and keywords for papers, standards, and technical guidelines.

After the further screening of full-text articles, 73 highly relevant journal articles were identified for this extensive review. The distribution of each topic within this finalised literature is outlined as follows. 60% of the papers dealing with different devices and operating strategies, which contain methods and devices for improving IAQ, such as mechanical ventilation, enhanced HVAC systems, the use of air purifiers, and optimising ventilation and cleaning strategies. 21% addressed measures related with structural changes, including green infrastructure (hedges, trees, plants, etc.), and renovation of the building and school facilities. 11% involved studies of sharing useful IAQ information for teacher and student/parent awareness. 8% is about policies which are successful in keeping air pollutants under legal limits. Dedication of a budget, introducing policies for school IAQ and procedures for monitoring and auditing, and creating clean zones are effective measures belonging to policies.

Measures related to devices and operating strategies take the largest proportion by classifying all measures. Natural ventilation is the most common type of ventilation system used in educational buildings, being predominant in many

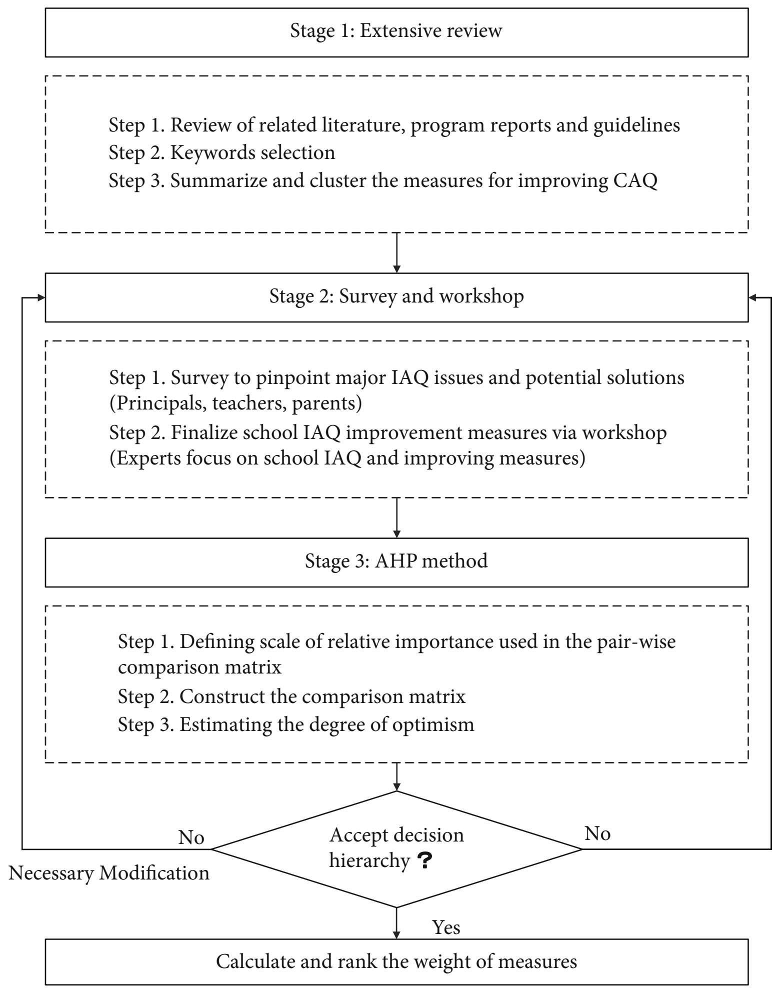



Figure 1: Framework for identification and ranking the measures using AHP method.

countries and regions, like the US, the UK, Southern and Southeastern Europe, China, India, and Australia [23, 52]. Strategies to optimise natural ventilation, such as controlling the opening of windows and doors, are effective measures to improve IAQ [53–57]. The automatic system for window openings considering IAQ correlations has been raised to guarantee air quality [54]. Numerous schools are located in areas with high levels of air pollutants [42, 58, 59]. Taking into account the poor outdoor air quality, mechanical ventilation or air purifiers should be added to improve IAQ. Air purifiers have been proven to be effective in reducing air pollutants, especially particulate matter [27, 60, 61]. Although natural ventilation has several benefits, the level of indoor airborne particles can be higher in naturally ventilated buildings by the penetration of outdoor particles through openings and leaks in the building envelope [62]. Compared with natural ventilation, mechanical ventilation can be effective in removing air pollutants [20, 63–65]. While considering the cost of equipment and operational energy consumption, a fan filter unit is a good filtration strategy [65, 66]. Besides, the cleaning and maintaining of the HVAC system is also important to avoid being a pollution source and prevent dust from spreading again [67–69].

Infrastructural measures mainly focus on the use of green infrastructure, school building renovation, and upgrading school facilities. Green infrastructure (GI) encompasses a network of managed vegetation that includes trees, hedges, green roofs, green walls, and green barriers or "fences" composed of narrow lines of mixed vegetation [70]. The presence of potted plants likely favoured a decrease of approximately 30% in $PM_{10}$ concentrations [71]. Greenness within and surrounding school boundaries can result in lower indoor and outdoor levels of traffic-related air pollutants (TRAPs) including $NO_2$, ultrafine particles, black carbon, and traffic-related $PM_{2.5}$ [72]. Besides the potential for air quality betterment, the social cobenefits of implementing a green fence in the school were particularly dominant [70]. The green roof system can reduce local particle concentrations [73], but more evidence is needed regarding the capability of green roofs to improve CAQ [74, 75]. The "Toolkit of Measures to Improve Air Quality at Schools" by the Mayor of London, UK, has suggested several measures to plan GI in schools, situated in the most polluted areas of London [76]. Substantial renovations (including new heating, ventilation, air-conditioning systems, and window replacement) show significant improvement in IAQ [77]. Replacement of building materials and furniture is also a strategy that belongs to structural measures [78, 79]. The carpeted floor with hard tiles, proper selection of cleaning products, and fleecy cleaning cloth introduced in the classroom can limit exposure to TVOCs [80]. Physical defects in the school building, such as cracks and holes in the walls, broken windows, and peeling wallpaper or paint, were associated with higher indoor NO2 concentrations [81]. Mould growth in school buildings can cause absenteeism and health problems in students [82]. Fixing leaky plumbing and building envelopes (i.e., roofs, walls, and floors) could be effective in preventing mould growth [83]. Therefore, school renovation to improve building infrastructure and IAQ leads to health and academic benefits for students and teachers.

Establishing appropriate policies and regulations is an essential part of improving school air quality. Some government organizations and programs developed measures, guidelines, and/or regulations to improve school IAQ, such as the EPA guidance document [84], building bulletins related to school buildings [85], and WHO global air quality guidelines [86]. In addition, the SINPHONIE project developed guidelines and general recommendations for IAQ improvement school environment [87]. On the other hand, the United States Environmental Protection Agency (USEPA) has also been working on the implementation of IAQ mitigation measures by distributing an action kit called "Tools for Schools Action Kit" to public schools, teachers and health professionals, and students and their parents/guardians [27]. The Mayor of London has rolled out an ambitious plan to control the rising levels of air pollutants near schools by introducing the world's first Ultra Low Emission Zone (ULEZ) in Central London [76]. The introduction of clean air zones can be created through school streets, anti-idling campaigns, and more appropriate locations of drop-off and pick-up points [88–91]. Local road layout changes and careful selection of new sites for schools and restricting the most polluting vehicles around schools have also been proposed as key methods by which children's exposure can be reduced [87, 90, 92]. To promote the implementation of the policy and support the necessary infrastructure changes, a sufficient budget is needed to improve school air quality [76, 93]. The regulation of the indoor environment is also important. In France, in the context of the French environmental program, "Grenelle Environment," mandatory requirements were developed for the regular monitoring and auditing of IAQ in schools [94]. Based on the collected data on policies aimed at improving the environment in schools and kindergartens, a report published by WHO European Centre for Environment and Health showed that procedures for investigating and addressing complaints about the smell of chemical pollutants have been conducted for 6 counties [94]. Meanwhile, designating an IAQ coordinator to check on clean air measures could be an effective way to ensure a good IAQ [95, 96].

Sharing IAQ information with teachers and pupils/parents helps them to take action to improve the air quality [31]. People seldom recognize a worsening of their IAQ since many air pollutants, being colourless and odourless, are impossible to detect with unaided human sensors [97]. IAQ visualization must effectively turn numeric air quality data into a meaningful representation of information so that users can easily understand what is happening to their IAQ (awareness), what it means to them (understanding), and what to do with the information (action) [30, 31]. In addition, reporting the IAQ regularly is a good way to offer useful information to teachers and parents [84]. To make a positive change towards cleaner air, a joint effort is needed to involve all civil society actors. Citizen science gives learners an insight into the ways that scientists generate solutions for societal problems. The school environmental education programs have proven to be successful in engaging young children in creating their scientific experiments eliciting ideas and increasing knowledge about air pollution among the participating students [98, 99].

According to the analysis above, the potential measures for improving school IAQ are summarized in Table 1.

As discussed above, there are multiple measures available at various scales for improving the IAQ. These measures require interventions at multiple aspects, including policy, device, operation strategy, infrastructural change, and information sharing. According to the different implementation stages of the various measures, we have categorised them into three categories, namely, policy, technology, and information sharing (see Figure 2). "Device and operating strategy" and "infrastructural change" have been combined in the broad category of "technology" as they are both technologically related and have essentially the same stage of implementation. Policies are usually implemented upfront to guide a range of subsequent measures. With the policy guidance in the early stages, technological measures began to be implemented to improve indoor air quality by selecting appropriate measures for different schools. Useful IAQ information sharing in indoor spaces will help in understanding the risk hours and hence will alarm the occupants to take necessary precautions against the transmission. An effective IAQ information sharing system is much needed to identify and monitor these parameters dynamically in indoor spaces to effectively maintain the IAQ. Meanwhile, it can give effective feedback on the effectiveness of the implementation of previous policies and technological measures, thereby improving the health and well-being of the individuals in classrooms.

*2.3. Stage 2—Determine Key Action Measures.* First, the pre-research open-ended questionnaire surveys collected 80 participants focused on the problems in CAQ, and expected solutions were sent to a decision group comprising school principals, teachers, and parents. Some basic information has been surveyed and recorded, including the CAQ situation, the implementation of existing indoor environmental improvement measures, and the acceptance of the measures that can be implemented. Regarding the HVAC systems in the surveyed classrooms in China, 45.7% of the classrooms were equipped with air-conditioning systems. Therefore, proper cleaning of the HVAC system is a measure that should be considered. In terms of ventilation behaviours, during the summer months, 70.4% of respondents will keep their windows and doors open all the time, and only 2.4% will choose to close them usually, while 27.2% will choose to keep them open some of the time. During the winter,

Table 1: Measures improving CAQ.

| Ord | Indicator | Reference |
|---|---|---|
| *Category I: policy* | | |
| 1 | Dedication of a budget from the government to improve IAQ in primary schools | [76, 93] |
| 2 | Introducing a school policy for CAQ | [87, 94, 100] |
| 3 | Introducing a procedure for monitoring and auditing the CAQ | [94] |
| 4 | Restricting the most polluting vehicles around schools and pedestrianisation by school entrances | [76, 87] |
| 5 | Creating clean air zones through school streets, anti-idling campaigns, and more appropriate locations of drop-off and pick-up points | [88–91] |
| 6 | Local road layouts changes and careful selection of new school sites | [76, 90] |
| 7 | Designate an IAQ coordinator to check on clean air measures | [93, 94] |
| *Category II: device and operating strategy* | | |
| 8 | Using natural ventilation to improve IAQ (e.g., opening window) | [55, 56] |
| 9 | Using natural ventilation together with indoor air purifiers to improve IAQ | [27, 60, 61, 101] |
| 10 | Using mechanical ventilation to improve the IAQ in classrooms | [64, 65, 86] |
| 11 | Regular housekeeping in classrooms and regular cleaning of the air supply equipment to enhance IAQ | [87, 100, 102] |
| 12 | Improve ventilation behaviour patterns and cleaning practices | [57, 103, 104] |
| 13 | Place fans in windows to exhaust room air to the outdoors | [66] |
| *Category III: infrastructural change* | | |
| 14 | Providing green infrastructure to reduce outdoor pollution and enhance IAQ (e.g., green hedges and plants) | [70, 71, 76, 91, 105] |
| 15 | Introducing new HVAC systems | [77] |
| 16 | Replacement of building materials, furniture, and windows | [77–79] |
| 17 | Renovation of building envelopes | [83] |
| *Category IV: information sharing* | | |
| 18 | Sharing on-screen display of the status of IAQ for teachers/pupils and parents | [30, 31] |
| 19 | Reporting the IAQ regularly in the school meetings and communicating the action plans to enhance IAQ in classrooms | [84] |
| 20 | Awareness raising of the importance and influence of the IAQ in schools and children | [98, 99] |

the percentage of people who keep their windows and doors open all the time is considerably lower, with only 33.33% choosing to keep them open all the time. As can be seen from the above, the occupants do not have a good strategy for the control of ventilation. Considering the reasons for opening windows and doors, bringing in the fresh air, feeling stuffy, and feeling hot are the top three reasons for opening the windows and doors. It can be concluded that natural ventilation is considered to be an important means of improving the indoor environment. Intensified cleaning has been proven to be effective in improving IAQ [106]. Through analysis of the data collected, 82.5% of classrooms have a daily floor cleaning frequency. However, 13.8% of classrooms still have their floors cleaned once a week. As a result, classroom cleaning strategies still need to be improved. The results of the acceptance of measures to be implemented were analysed. 86.3% of participants considered it necessary to provide an on-screen display of the status of IAQ in classrooms. 80% of participants believed that the limited funds available to schools needed to be used to improve IAQ. By analysing the data collected, emphasis was given to the limitations of existing improvement measures, including ventilation and cleaning methods, and the urgent need for respondents to improve the quality of the indoor environment.

Following the first part of the screening, the project team organized a number of workshops to finalise the CAQ improvement measures based on the outcomes from the previous stage. Finally, the indicators are derived by the following rules: (1) feasibility to attain the value of the measurement indicator. According to the relevant study, technological changes are the most expensive and complex measures [107]. We should be very careful when we choose the final measures that belong to these two categories. For example, "introducing new HVAC systems" is too expensive to be universally implemented. Therefore, "introducing new HVAC systems" is discarded as an indicator. (2) Complete rule means that the identified indicator list should cover the main aspects of prioritising actions for improving school CAQ. (3) Effective rule means that the identified indicator list should ignore the minimum issues that have minimum impact on the prioritising actions for improving school CAQ. (4) Multiply attributes decision-making (MADM) rules. Then, the hierarchy structure is formed such that the objective is at the first level, measure categories are at the second level, and specific measures are at the third level (see Figure 3).


Figure 2: Classification of different types of measures for improving school IAQ and their methodologies.

### 2.4. *Stage 3—AHP Questionnaire Design and Determining Weights for Each Measure*

*2.4.1. Comparison Matrix Construction and Index Calculation.* In AHP, assessors judge the importance of measures through pairwise comparison of measures[108]. The importance scale suggested by Saaty [44] has been used to determine the values of AHP pairwise comparisons, as demonstrated in Table 2. This allows the respondent to assign relative priority when comparing two elements [109]. The respondents can express their preference between every two elements and can translate the description or definition of the preferences into numerical ratings of 1, 3, 5, 7, and 9 and into 2, 4, 6, and 8 as intermediate values.

This research focused on a subjective weighting method to determine the preference for air quality indicators. This study adopted a pairwise comparison approach proposed in AHP method. Following the AHP subjective weight calculation method, the weight vector is developed using the principle of the eigenvector.

For $n$ measures, the pairwise comparison matrix $A$ of these measures is determined as follows:

$$A = \begin{matrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{matrix} \begin{bmatrix} a_{11} = \frac{I_1}{I_1} & a_{12} = \frac{I_1}{I_2} & \cdots & a_{1n} = \frac{I_1}{I_n} \\ a_{21} = \frac{I_2}{I_1} & a_{22} = \frac{I_2}{I_2} & \cdots & a_{2n} = \frac{I_2}{I_n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} = \frac{I_n}{I_1} & a_{n2} = \frac{I_n}{I_2} & \cdots & a_{nn} = \frac{I_n}{I_n} \end{bmatrix}. \quad (1)$$

Matrix $A$ represents the pairwise comparison of measures ($I$) with respect to each measure. For matrix $A$, each element represents the relative preference of one measure over another. For instance, the element situated in the first row and second column "$a_{12} = I_1/I_2$" represents the relative priority (i.e., importance) of the first measure over the second one. If the first measure ($I_1$) is extremely important than

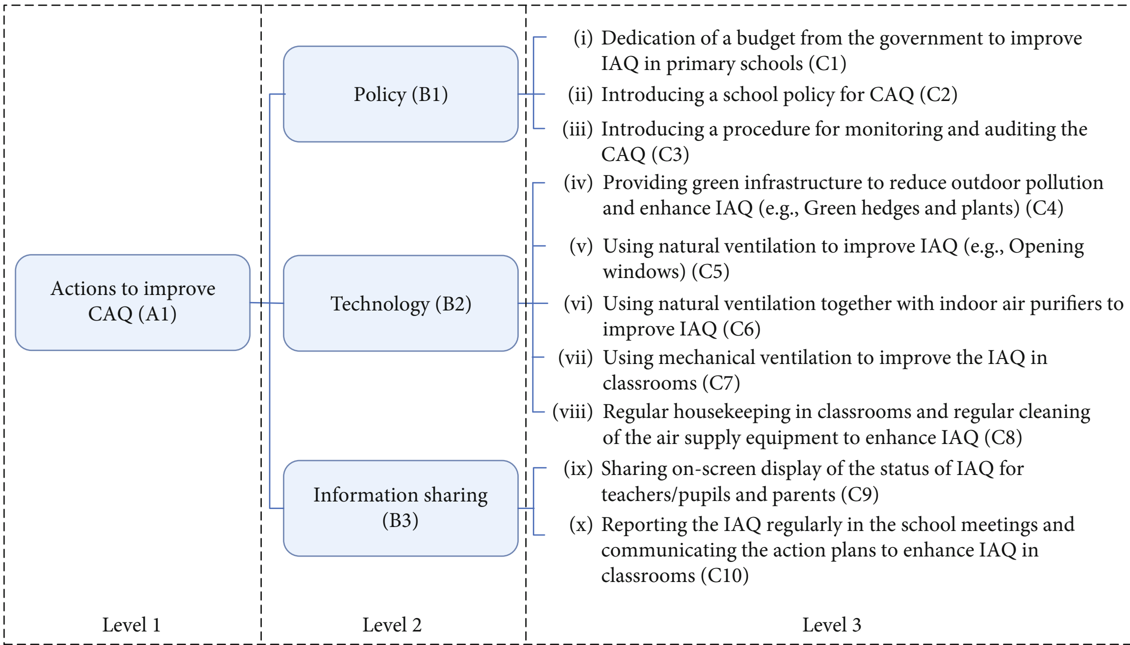



Figure 3: Measures for improving CAQ.

Table 2: The fundamental scale for pairwise comparison [44].

| Intensity of importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two activities contribute equally to the objective |
| 3 | Weak importance of one over another | Experience and judgment slightly favour one activity over another |
| 5 | Essential or strong importance | Experience and judgment strongly favour one activity over another |
| 7 | Demonstrated importance | An activity is strongly favoured and its dominance demonstrated in practice |
| 9 | Absolute importance | The evidence favouring one activity over another is of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values between the two adjacent judgments | When compromise is needed |
| Reciprocals | If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i* | |

the second one ($I_2$), then the relative importance ($a_{12}$) of these two measures would be represented using the following equations.

$$a_{12} = \left(\frac{I_1}{I_2}\right) = 9, \tag{2}$$

$$a_{21} = \left(\frac{I_2}{I_1}\right) = \frac{1}{9}. \tag{3}$$

To determine the subjective weight of each measure, the eigenvalue approach was adopted. The general eigenvalue is obtained through perturbation of the following formulation:

$$\begin{bmatrix} \frac{I_1}{I_1} & \frac{I_1}{I_2} & \cdots & \frac{I_1}{I_n} \\ \frac{I_2}{I_1} & \frac{I_2}{I_2} & \cdots & \frac{I_2}{I_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{I_n}{I_1} & \frac{I_n}{I_2} & \cdots & \frac{I_n}{I_n} \end{bmatrix} \bullet \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lambda_{\max} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix}. \tag{4}$$

In equation (3), $W$ is the vector of weights (eigenvector) $W = (w_1, \cdots, w_n)$ and $\lambda_{\max}$ represents the principal eigenvalue of the pairwise comparison matrix $A$ [110].

Furthermore, to ensure the consistency of the subjective perception and the accuracy of comparative weights, Saaty [44] suggests employing a consistency index (CI) and a consistency ratio (CR). To define CI and CR for pairwise comparison matrix $A$, the following equations were introduced [111]:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}, \quad \mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{5}$$

where $n$ denotes the number of measures and RI represents the random consistency index that was introduced by Saaty and Sodenkamp [112] shown in Table 3. For reliable results, the consistency ratio (CR) should not exceed 0.10 [113].

The last step in the AHP process is to combine individual judgments into a single aggregate group judgment.

To aggregate the comparison matrices from individual respondents, the geometric mean approach is adopted in this study for each level using an aggregated comparison matrix as follows [43].

$$A_{\text{group}} = \begin{bmatrix} \sqrt[m]{a_{(11)_1} \times a_{(11)_2} \times, \cdots, a_{(11)_m}}, & \sqrt[m]{a_{(12)_1} \times a_{(12)_2} \times, \cdots, a_{(12)_m}} & \cdots & \sqrt[m]{a_{(1n)_1} \times a_{(1n)_2} \times, \cdots, a_{(1n)_m}} \\ \sqrt[m]{a_{(21)_1} \times a_{(21)_2} \times, \cdots, a_{(21)_m}}, & \sqrt[m]{a_{(22)_1} \times a_{(22)_2} \times, \cdots, a_{(22)_m}}, & \cdots & \sqrt[m]{a_{(2n)_1} \times a_{(2n)_2} \times, \cdots, a_{(2n)_m}} \\ \vdots & \vdots & \ddots & \vdots \\ \sqrt[m]{a_{(n1)_1} \times a_{(n1)_2} \times, \cdots, a_{(n1)_m}}, & \sqrt[m]{a_{(n2)_1} \times a_{(n2)_2} \times, \cdots, a_{(n2)_m}}, & \cdots & \sqrt[m]{a_{(nn)_1} \times a_{(nn)_2} \times, \cdots, a_{(nn)_m}} \end{bmatrix}. \tag{6}$$

For this formula, $A_{\text{group}}$ represents a group comparison matrix for measures, $m$ is the number of experts involved in judgments, and $a$ is the relative importance between $i$ and $j$ in matrix $A$, as evaluated by an expert. Each row of the matrix $A_{\text{group}}$ identifies the ratios of the weights of each indicator concerning all others.

## 3. Results and Discussion

In this study, 98 and 40 respondents from China and the UK, respectively, participated in the questionnaire survey to identify and prioritise the measure to improve IAQ in schools. A total of 138 questionnaires returned, out of 129 were valid (valid rate 93.5%). China experiences a warmer and more humid climate, necessitating reliance on mechanical ventilation and air-conditioning, in contrast to the UK's milder climate, where natural ventilation is more feasible. Of the valid questionnaires, 70 questionnaires were completed by purple's parents, and 54 questionnaires were completed by teachers.

*3.1. Consistency Adjustment for Matrix CR Values.* In order to make the conclusion more credible, this paper uses Zhang's consistency adjustment method called GAOHP [114] to adjust the matrix that fails to pass the consistency judgment. The algorithm is based on the genetic algorithm, which transforms the matrix consistency problem into the optimal solution problem, fully retaining the decision-maker's judgment intention. The author also develops the corresponding MATLAB application program. After consistency adjustment, the matrix in this paper passes the consistency judgment. As shown in Figure 4, $\mathrm{CR} < 0.1$ for all matrices after consistency adjustment (m1 is the judgment matrix representing level 2, m2 is the judgment matrix representing the policy part of level 3, m3 is the judgment matrix representing technology (B2) in level 3).

Moreover, the sample size of the subjects determines the credibility of judgment and the consistency of judgment. The judgement of the indicators' priority is very reliable as long as the consistency ratio (CR) is less than 0.1. Figure 5 demonstrates the CR trends of group comparison matrices. Figure 5 shows the CR decreases with the incensement in the number of subjects. And the CR stabilises maintained when the subject size is greater than 20. Thus, the sample size of over 20 subjects in this survey is sufficient to ensure the credibility of the judgment. In this study, the sample size for both China and the UK exceeds the threshold with 98 from China and 40 from the UK.

Besides, the CR values of the pairwise comparison matrices are depicted in Figure 6. There are only two sub-indicators in "information sharing (B3)." Therefore, the consistency problem does not exist in category B3. Figure 6 suggests that the CR values are all smaller than 0.1, meaning that the consistency levels of the pairwise comparison matrices are acceptable, and the data analysis is convincing.

*3.2. Pairwise Comparison Matrix.* By using the scaled response of the respondents and the consistency adjustment, various CAQ improvement measures are compared, and the results are shown in Figure 1. These matrices capture the relative weights as perceived in China (a) and the UK (b). Values above 1 denote higher importance, while values below 1 denote lesser importance. The pairwise comparison matrices on the two tiers of the hierarchic structure illustrated in Figure 1 are obtained as follows:

(1) Comparison matrix of B1, B2, and B3 ($n = 3$) with China (a) results in the left and the UK (b) results in the right

Table 3: Random index (RI) values.

| Number of criteria | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0.0 | 0.0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 | 1.52 | 1.54 | 1.56 | 1.58 | 1.59 |

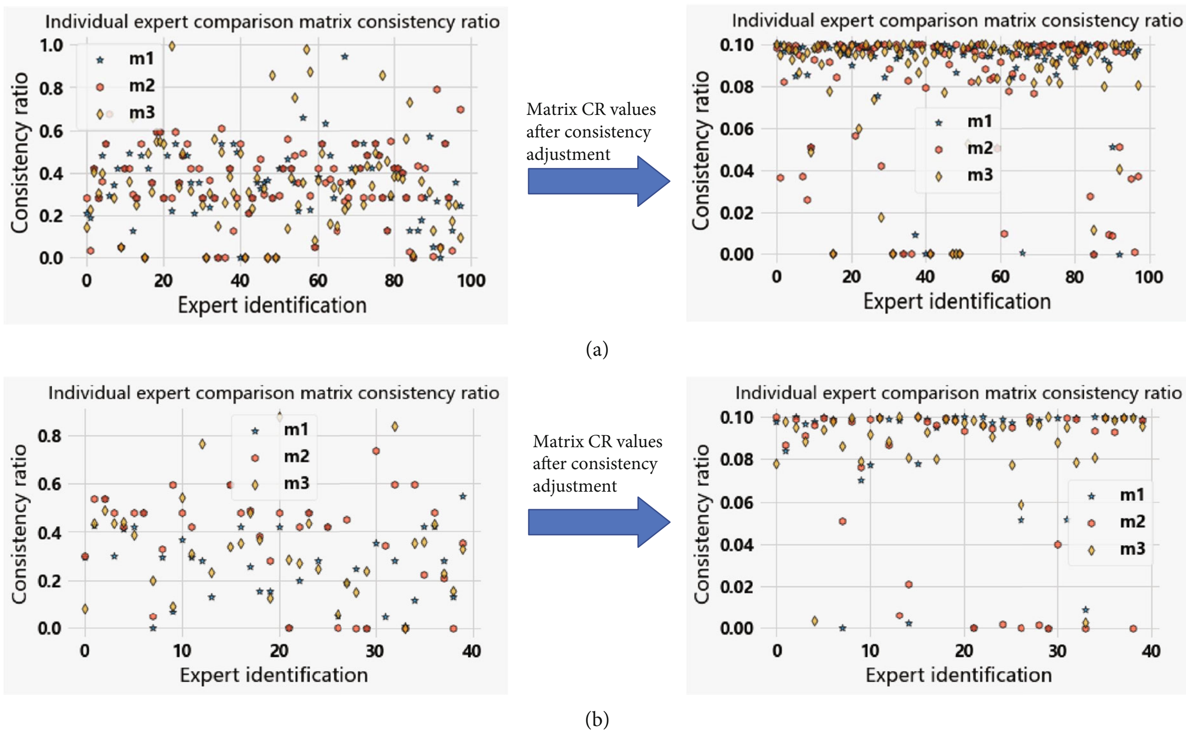



Figure 4: Consistency adjustment for matrix CR values: (a) China survey and (b) UK survey.

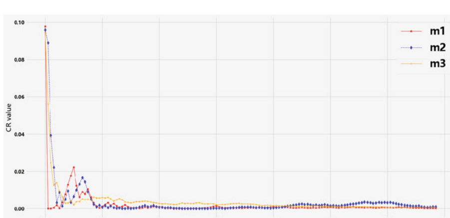



Figure 5: The relationship between the number of experts used in the level comparison matrices and the consistency ratio.

$$\begin{bmatrix} 1.000 & 0.522 & 0.626 \\ 1.915 & 1.000 & 1.122 \\ 1.598 & 0.891 & 1.000 \end{bmatrix} \quad \begin{bmatrix} 1.000 & 0.610 & 1.849 \\ 1.640 & 1.000 & 2.724 \\ 0.541 & 0.367 & 1.000 \end{bmatrix}$$

(a) (b)

(2) Comparison matrix of C1, C2, and C3 ($n = 3$) in China (a) and the UK (b)

$$\begin{bmatrix} 1.000 & 1.143 & 0.777 \\ 0.875 & 1.000 & 0.579 \\ 1.287 & 1.727 & 1.000 \end{bmatrix} \quad \begin{bmatrix} 1.000 & 1.700 & 1.483 \\ 0.588 & 1.000 & 1.045 \\ 0.674 & 0.957 & 1.000 \end{bmatrix}$$

(a) (b)

(3) Comparison matrix of C4, C5, C6, C7, and C8 ($n = 5$) in China (a) and the UK (b)

$$\begin{bmatrix} 1.000 & 1.534 & 1.087 & 1.225 & 1.153 \\ 0.652 & 1.000 & 0.709 & 0.830 & 0.712 \\ 0.920 & 1.411 & 1.000 & 1.168 & 1.059 \\ 0.816 & 1.205 & 0.856 & 1.000 & 1.021 \\ 0.867 & 1.404 & 0.944 & 0.979 & 1.000 \end{bmatrix} \quad \begin{bmatrix} 1.000 & 1.199 & 0.679 & 1.025 & 1.011 \\ 0.834 & 1.000 & 0.343 & 0.754 & 0.872 \\ 1.472 & 2.918 & 1.000 & 1.898 & 2.159 \\ 0.975 & 1.327 & 0.527 & 1.000 & 1.250 \\ 0.989 & 1.147 & 0.463 & 0.800 & 1.000 \end{bmatrix}$$

(a) (b)

(4) Comparison matrix of C9 and C10 ($n = 2$) in China (a) and the UK (b)

$$\begin{bmatrix} 1.000 & 1.244 \\ 0.804 & 1.000 \end{bmatrix} \quad \begin{bmatrix} 1.000 & 2.009 \\ 0.498 & 1.000 \end{bmatrix}$$

(a) (b).

*3.2.1. Results of Main Measures in Level Two.* Based on the pairwise comparison matrices generated and the processing method described previously, the calculated weight factors are obtained, as presented in Figure 7. It can be seen that "technology (B2)" has the highest priority measure of 0.417 wt and 0.504 wt in China and the UK, respectively, followed by the other two main indicators "policy (B1)" and "information sharing (B3)," indicating that of the three main measures, the technology is the paramount indicator in relation to the "actions to improve CAQ (A1)" level. It

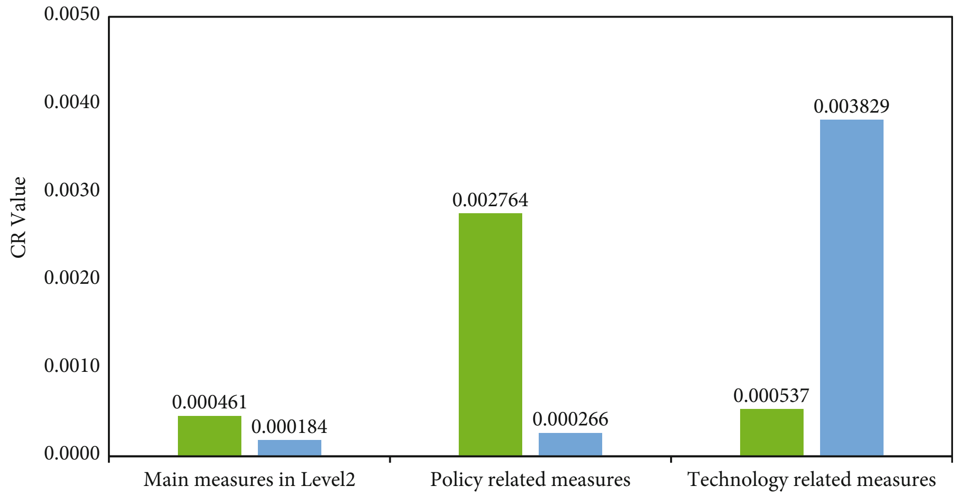



Figure 6: The consistency ratio of the pairwise comparison matrices (green for China and blue for the UK).

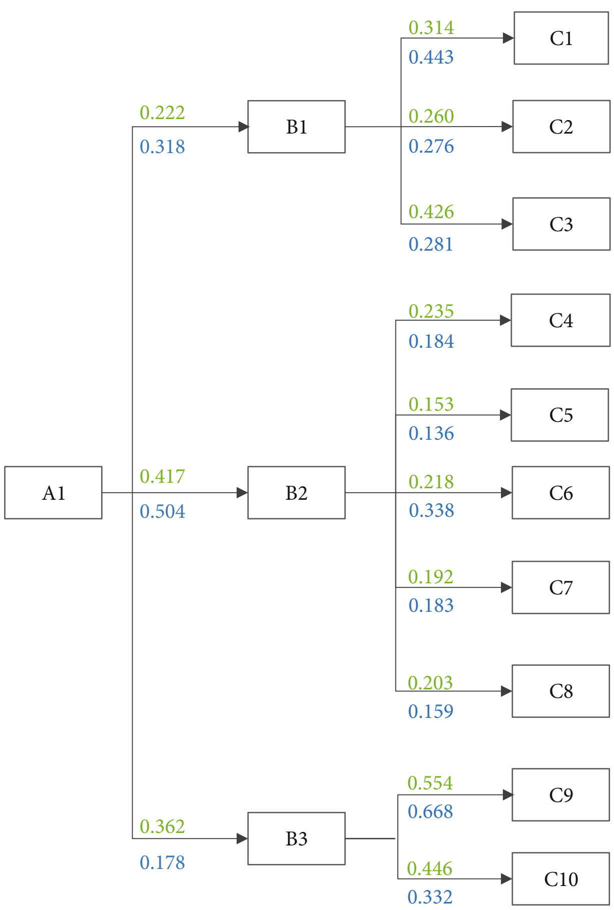



Figure 7: Priority factors of the hierarchic structure (green for China and blue for the UK).

indicates that the implementation of technologies for improving CAQ is highly expected by school stakeholders. Besides, the effects of indicators "policy (B1)" and "information sharing (B3)" are with the respective weight of 0.222/0.318 and 0.362/0.178 from China and the UK school surveys.

The analysis implies that the "technology (B2)" should evaluate when considering CAQ improvement since B2 had the highest impact on the CAQ improvement and got nearly half weightage.

For the China group of submeasures affiliated with the policy (B1), the ranking order of submeasure is C3 > C1 > C2. "Introducing a procedure for monitoring and auditing the CAQ (C3)" obtained 0.426 wt, followed by "dedication of a budget from the government to improve IAQ in primary schools (C1)" with 0.314 wt and "introducing a school policy for CAQ (C2)" with 0.260 wt. Meanwhile, from the UK perspective, the ranking order of submeasure is C1 > C3 > C2. The C1 becomes a key submeasure for policy formulation and implementation, while the impact on C3 and C2 is considered as least important with divided 0.276 and 0.281 equally.

Moreover, regarding the submeasures related to the technology (B2), in China, the ranking of submeasure order is C4 > C6 > C8 > C7 > C5. "Providing green infrastructure to reduce outdoor pollution and enhance IAQ (e.g., green hedges and plants) (C4)" has the highest weighting factor of 0.235. "Using natural ventilation together with indoor air purifiers to improve IAQ" (C6) is slightly lower than C4. While in British, the ranking is C6 > C4 > C7 > C5 > C8. "Using natural ventilation together with indoor air purifiers to improve IAQ" (C6) as the highest weight is 0.338, followed by 0.184 for C4 and 0.183 for C7 (using mechanical ventilation to improve the IAQ in classrooms). It is also noteworthy that the least essential subfactors for C5 and C8 (regular housekeeping in classrooms and regular cleaning the air supply equipment to enhance IAQ) are 0.136 and 0.159, respectively.

Furthermore, when it comes to the group of "information sharing (B3)" measures, the ranking order of submeasures is C9 > C10 similarly. "Sharing on-screen display of the status of IAQ for teachers/pupils and parents (C9)" ranked priority by obtaining 0.554 and 0.668 wt in China and the UK. The weighting of C9 is over 10%-20% than that of "reporting the IAQ regularly in the school meetings and communicating the action plans to enhance IAQ in classrooms (C10)."

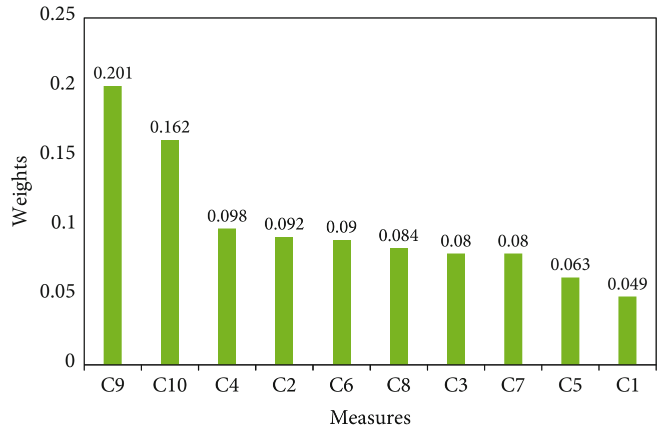



Figure 8: Weights of submeasures for improving CAQ in China. C9: sharing on-screen display of the status of IAQ for teachers/pupils and parents; C10: reporting the IAQ regularly in the school meetings and communicating the action plans to enhance IAQ in classrooms; C4: providing green infrastructure to reduce outdoor pollution and enhance IAQ (e.g., green hedges and plants); C2: introducing a school policy for CAQ; C6: using natural ventilation together with indoor air purifiers to improve IAQ; C8: regular housekeeping in classrooms and regular cleaning of the air supply equipment to enhance IAQ; C3: introducing a procedure for monitoring and auditing the CAQ; C7: using mechanical ventilation to improve the IAQ in classrooms. C5: using natural ventilation to improve IAQ (e.g., opening windows); C1: dedication of a budget from the government to improve IAQ in primary schools.

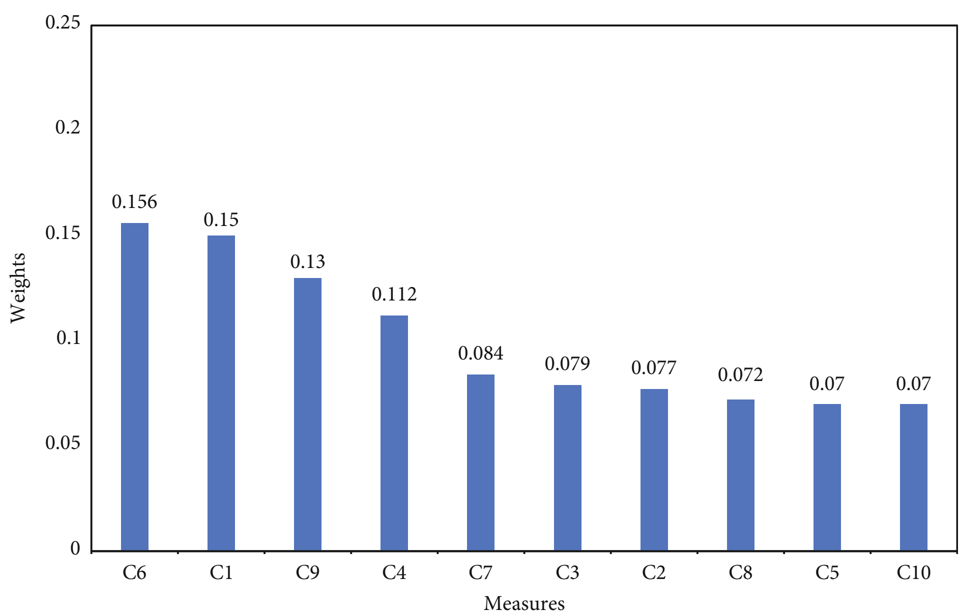
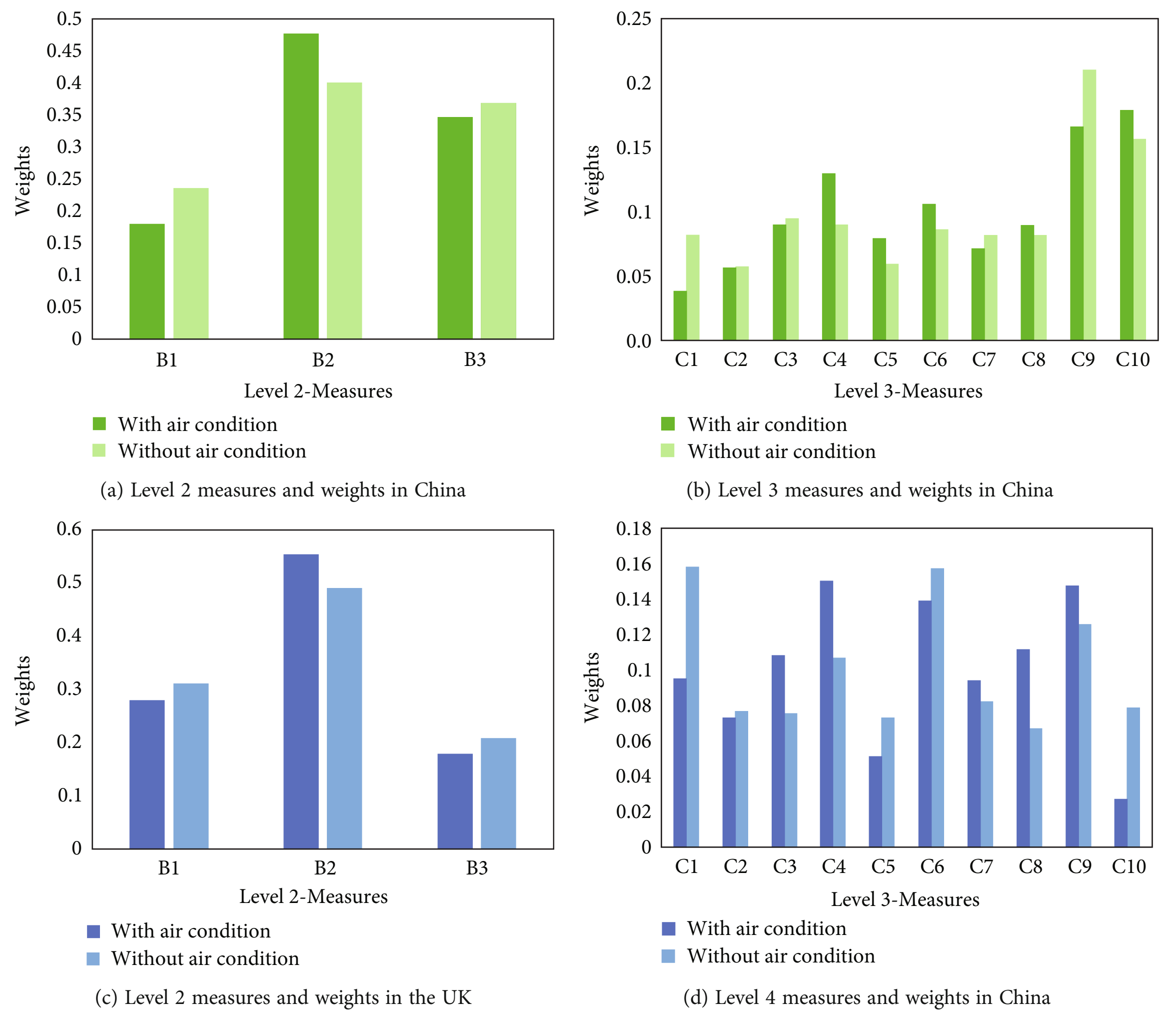



Figure 9: Weights of submeasures for improving CAQ in the UK. C6: using natural ventilation together with indoor air purifiers to improve IAQ; C1: dedication of a budget from the government to improve IAQ in primary schools; C9: sharing on-screen display of the status of IAQ for teachers/pupils and parents; C4: providing green infrastructure to reduce outdoor pollution and enhance IAQ (e.g., green hedges and plants); C7: using mechanical ventilation to improve the IAQ in classrooms; C3: introducing a procedure for monitoring and auditing the CAQ; C2: introducing a school policy for CAQ; C8: regular housekeeping in classrooms and regular cleaning of the air supply equipment to enhance IAQ; C5: using natural ventilation to improve IAQ (e.g., opening windows); C10: reporting the IAQ regularly in the school meetings and communicating the action plans to enhance IAQ in classrooms.

*3.2.2. Results of Submeasures in Level Three.* The final weight and ranking of submeasures were determined by multiplying each subcriterion priority weight of its respective main measures. The evaluation and ranking of 10 submeasures were performed with respect to the goal. This step develops the overall priority of the 10 submeasure in China and the UK, respectively.

The ranking of submeasures and the weights of ten measures for improving CAQ within China are presented in Figure 8. The highest two measures, C9 and C10, are in the aspects of "information sharing (B3)." "Sharing on-screen display of the status of IAQ for teachers/pupils and parents (C9 )" has been identified as the most important submeasure with 0.201 wt. Especially for teachers who spend




(a) Level 2 measures and weights in China

(b) Level 3 measures and weights in China

(c) Level 2 measures and weights in the UK

(d) Level 4 measures and weights in China

Figure 10: Indicator weights obtained from questionnaires accomplished by respondents from classrooms with and without air-conditioning (green bar charts for China and blue bar charts for the UK). B1: policy; B2: technology; B3: information sharing; C1: dedication of a budget from the government to improve IAQ in primary schools; C2: introducing a school policy for CAQ; C3: introducing a procedure for monitoring and auditing the CAQ; C4: providing green infrastructure to reduce outdoor pollution and enhance IAQ (e.g., green hedges and plants); C5: using natural ventilation to improve IAQ (e.g., opening windows); C6: using natural ventilation together with indoor air purifiers to improve IAQ; C7: using mechanical ventilation to improve the IAQ in classrooms; C8: regular housekeeping in classrooms and regular cleaning of the air supply equipment to enhance IAQ; C9: sharing on-screen display of the status of IAQ for teachers/pupils and parents; C10: reporting the IAQ regularly in the school meetings and communicating the action plans to enhance IAQ in classrooms.

a lot of time in the classroom, an on-screen display of the status of IAQ is more convenient for them to get the relevant Information. "Reporting the IAQ regularly in the school meetings and communicating the action plans to enhance IAQ in classrooms (C10)" comes as the second significant submeasure with 0.162 wt. The rest of the submeasures in technology (B2) and policy (B1) ranked gradually from 0.098 to 0.049 wt. The reason of this following results might because green plants and communication are the first two needed things in Chinese perspectives. Green plants were considered as one of the key government development strategies. Reporting and communicating about IAQ benefits the improvement of air quality.

Figure 9 presents the weight of measures for improving CAQ in the UK. "C6: using natural ventilation together with indoor air purifiers to improve IAQ" is reported as the most important economic measure by obtaining 0.156 wt. Chartered Institution of Building Services Engineers (CIBSE) standards [115] suggested that natural ventilation with air purifiers is protective in the pandemic era; thus, school stakeholders ranked the C6 submeasure as the most important factor. The second highest submeasure within CAQ is 'C1: dedication of a budget from the government to improve IAQ in primary schools" with 0.150 wt. In the UK, given the varied living experiences and heightened public media awareness, school stakeholders prioritize the combination of natural ventilation with air purifiers and an increased budget. This priority reflects not just educational needs but also concerns heightened by British media coverage on government financial issues. Moreover, "C9: sharing on-screen display of the status of IAQ for teachers/pupils and parents" and "C4: providing green infrastructure to reduce outdoor pollution and enhance the IAQ (e.g., green hedges and plants)" also got a considerable weight of 0.130 and 1.112 because passive measures are also very important for the effectiveness of CAQ development, while other submeasures shared the respective weights around 0.07 to 0.08.

*3.3. Results of with/without Air-Conditioning Systems in Classrooms.* The presence or absence of air-conditioning in classrooms influenced the results of the questionnaire. In China, the number of questionnaires for respondents from classrooms with and without air-conditioning was 77 and 21, respectively, out of the total number of questionnaires, while the number is 5 and 35 in the UK. Figure 10 displays the weights obtained from the questionnaires accomplished by respondents from classrooms with and without air-conditioning.

As can be seen from Figures 10(a) and 10(c), the technology (B2) is ranked highest according to the answers from respondents regarding classrooms with air-conditioning for level 2. Respondents from classrooms without air-conditioning also considered the B2 as the most important aspect. From Figure 10(b), "C9: sharing on-screen display of the status of IAQ for teachers/pupils and parents" is ranked highest for respondents from classrooms without air-conditioning. "C10: reporting the IAQ regularly in the school meetings and communicating the action plans to enhance IAQ in classrooms" is ranked highest for respondents from classrooms with air-conditioning. Compared with China questionnaire results, for level 3 in the UK, in the air-conditioning classroom, "providing green infrastructure (C4)" and "sharing on-screen display of the status of IAQ (C9)" receive equal weight. In classrooms without air-conditioning, "dedication of a budget to improve IAQ (C1)" and "using natural ventilation with air purifiers (C6)" received the same level of importance.

In summary, from the results obtained with or without air-conditioning classroom comparison, the ranking order suggests B2 as the essential main measure. And C9 is the submeasure that must be considered to improve CAQ further since it continuously ranks the top three of all submeasures.

## 4. Conclusions

This study is aimed at devising actionable guidance for policymakers, offering a structured approach to prioritise action measures that can significantly enhance classroom air quality (CAQ). A two-stage methodology framework was employed, initiated by an extensive literature review to identify crucial factors influencing CAQ. Following this, through open-ended questionnaire surveys and a series of workshop discussions, three main categories and subsequently ten measures were identified. The analytical hierarchy process (AHP) method was then utilized to prioritise these measures pivotal to CAQ.

The adaptability and versatility of the stakeholder engagement approach were demonstrated in different cultural and environmental contexts of schools in China and the UK. It was found that technology-based solutions are the most impactful way for CAQ enhancement in both regions. Further analysis revealed that policy-based improvements are more effective while information sharing solutions were preferred in China. Specifically, it was noted that UK respondents' towards combined natural ventilation with indoor air purifiers contrasts sharply with the Chinese emphasis on green hedges and plants as primary CAQ enhancers.

These differences distilled from this study underscored that solutions might not be universally applicable. Strategies for improving CAQ were suggested to be tailored, considering the specific environmental and infrastructural realities of each region. Consequently, the study advocated for a structured method that offers layered insights into CAQ dynamics, facilitating the selection of comprehensive interventions targeting CAQ improvement:

(1) Stakeholder engagement approach: this study developed a novel approach that actively involves experts and school users in the prioritising process. The method can be duplicated in any other region. The novelty of this approach is the stakeholder engagement to ensure the actionable measures for CAQ enhancement

(2) Identification of key CAQ improvement measures: through comprehensive literature review, questionnaire survey, and workshop to determine the understanding of the most commonly implemented measures for improving CAQ which provides a clear benchmark for best practices

(3) Prioritisation using AHP: the geometric mean approach-based AHP method is a proven practical multicriteria decision-making method in prioritisation. The ranking of the CAQ enhancement measures based on the proposed approach of this study provides policymakers with a detailed, data-driven roadmap for future interventions

This study demonstrates that actions are urgently needed to enhance classroom air quality. There is a limitation with the absence of a detailed cost and economic affordability analysis, though the focus of this study is more strategical level aiming at urging the CAQ enhancement actions. The performance of technologies and life cycle cost analysis for CAQ could be a potential for future studies. Additionally, the earlier version of this manuscript was presented at the "Healthy Buildings Europe" conference held from 11 to 14 July 2023.

## Data Availability

The data underlying this study is available upon request. Requests for access to the data should be directed to the corresponding author, Prof. Runming Yao, at r.yao@reading.ac.uk or r.yao@cqu.edu.cn.

## Disclosure

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## Conflicts of Interest

The authors declare that there is no conflict of interest.

## Authors' Contributions

Ziyu Shu and Feng Yuan (equal first authors) were responsible for the investigation, methodology, data curation, formal analysis, and visualization, wrote the original draft, and wrote, reviewed, and edited the manuscript. Jie Wang performed the research and analysed the data. Jian Zang specialized in the conclusion revision. Baizhan Li was responsible for the supervision, resources, and conceptualization. Mehdi Shahrestani was responsible for the UK questionnaire collection and manuscript review and editing. Emmanuel Essah was responsible for the manuscript review and editing. Hazim Awbi was responsible for the manuscript review. Mike Holland provided workshop guidance. Fangxin Fang was responsible for the expert workshop and manuscript review. Christopher Pain was responsible for the expert workshop and manuscript review. Prashant Kumar was responsible for the expert workshop. Hua Zhong was responsible for the expert workshop. Alan Short was responsible for the expert workshop. Paul Linden was responsible for the expert workshop. Runming Yao was responsible for the supervision, resource, and methodology and wrote, reviewed, and edited the manuscript.

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