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Indoor Air Quality Management and Mitigation Strategies in University Laboratories

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Abstract

Indoor air quality (IAQ) management is a systematic approach of managing and improving the indoor air quality in universities laboratories. An investigation of indoor air quality (IAQ) management and mitigation in university laboratory settings is conducted utilizing a mixed methods approach that blends bibliometric analysis with quantitative survey methods. This study aims to achieve two primary objectives: It first addresses the identification of potential sources of IAQ problems in university laboratories and the second one was to analyse the mitigation strategy to address these problems. A rigorous bibliometric analysis was conducted using VOSviewer software on 60 research papers published between year 2018 and 2024, revealing four main categories of IAQ concerns: Microbiological and biological contaminants, inadequate air circulation and supply, chemical pollutants and indoor particulate matter. To achieve the second objective, a quantitative survey was distributed to 69 respondents from Universiti Tun Hussein Onn Malaysia (UTHM) Pagoh. The most effective strategy used to deal with insufficient air circulation was to perform air balance in ventilation systems (94.4%), while chemical pollutants were dealt with by properly disposing outdated chemicals (93%). Management of microbiological contaminants by regular cleaning using environmentally friendly agents (94%) ranked highest, and removal of particulate matter by local exhaust ventilation systems (95.4%) was deemed best control measure. This analysis synthesizes a wealth of information on advanced IAQ management strategies in university laboratories. The results emphasize the need for proactively managing IAQ in university laboratories, and the need for systematic implementation of successful mitigation strategies. Universities can make academic and research environments healthier, safer by addressing identified sources of pollution and improving air quality practice practices.

1. Introduction

Indoor air quality (IAQ) is a critical yet often overlooked aspect of environmental health, particularly in educational settings such as university laboratories. As human activities continuously contribute to air pollution, the quality of the air we breathe indoors has become a pressing concern for public health. Research indicates that indoor air can be significantly more polluted than outdoor air, with levels of contamination potentially being five to a hundred times higher within enclosed spaces [1]. This alarming trend underscores the necessity for effective indoor air quality management and mitigation strategies, especially in environments where students and staff spend a considerable amount of their time. Indoor Air Quality (IAQ) Management Practices involve various techniques and technologies aimed at improving air quality in indoor environments, crucial for reducing pollutants and enhancing occupant health and comfort, especially highlighted during the COVID-19 pandemic through increased ventilation mandates (4).

Institutions are now exploring advanced monitoring methods to exceed local IAQ regulations [5][6]. In educational settings, guidelines emphasize mechanical ventilation and high-efficiency filtration to maximize breathable air, supported by organizations like ASHRAE and WHO, while also addressing occupancy rates and exposure duration (7, 8). Effective school IAQ management is a dynamic process that integrates key drivers into curricula for continuous improvement (18). In the workplace, Malaysia's DOSH established a Code of Practice on Indoor Air Quality in 2005 to ensure proactive risk assessments (18). Additionally, the rise of energy-efficient buildings necessitates robust ventilation solutions, with a trend toward mechanical systems in new constructions and retrofits, despite resident skepticism about their effectiveness (10, 11).

Recent scientific investigations have highlighted the detrimental effects of poor IAQ on cognitive performance and overall health. Studies have shown that inadequate ventilation and the presence of airborne contaminants can lead to various health issues, including respiratory problems and reduced productivity [2]. Despite this growing body of evidence, there remains a notable gap in research specifically addressing IAQ management in university laboratories. While many studies have focused on classrooms and office environments, the unique conditions present in laboratory settings—such as the use of hazardous materials and specialized equipment—demand targeted investigation [3]. Furthermore, existing literature often fails to provide comprehensive strategies tailored to enhance IAQ in these specialized environments.

Therefore, the study was aimed at achieving two primary objectives: first, potential sources of indoor air quality (IAQ) problems specific to university laboratories were identified; and second, effective mitigation strategies for managing these issues were analyzed. A mixed-methods approach was employed, combining bibliometric analysis to identify sources of IAQ problems with quantitative analysis to evaluate mitigation strategies.

2. List of Mitigation Strategies for Indoor Air Quality in University Laboratories

IAQ supports the guidelines in educational facilities and university classrooms that promote the optimisation of fresh air in spaces with mechanical ventilation. The past research paper agreed that the persist in adhering to such advice, which have resulted in higher energy costs [9]. From the literature review on the sources from references from books, standards guideline, journals, and previous studies, there is four main potential sources of problem for indoor air quality in university laboratories. The main potential sources that mentioned were inadequate air circulation and insufficient air supply (including room temperature, relative humidity, and air movement) [2], Nitrogen dioxide, Sulphur dioxide, Carbon monoxide, Ozone, Carbon dioxide, Total Volatile Organic Compounds, formaldehyde [12], Microbiological and biological contaminants [2][18] and Indoor air particulate matter (PM) levels [30]. Besides that, all the mitigation strategy for indoor air quality in University Laboratories related to the potential sources were explained in details in the table 1 below:

Table 1: List of mitigation strategy for IAQ in university laboratories

Potential sources of problem	Mitigation Strategy	References
Inadequate air circulation	1)Enhancing the quantity and enhancing the quality of ventilation. 2)Regular maintenance of ventilation systems, which includes the replacement of filters and the cleaning of ducts.	1.[2] 2)[18]
Chemical pollutants	1)By employing appropriate adsorbents like activated carbon and hydrophobic zeolites, adsorption 2)Low-cost sensor (LCS)-based Indoor Air Quality Monitoring System	1)[13] 2)[14] 3)[12] 4) [12] 5)[12] 6)[13][8]

	3)An air sampling system is utilised, consisting of a diaphragm vacuum pump called Pfeiffer MVP and manifolds with apertures 4)The Air Quality Egg V.2 and a customised, affordable air quality sensor device. 5)Implementing periodic intervals of non-occupancy in constructed spaces and advising all occupants to regularly exit the place for brief breaks. 6)Proper disposal of empty canisters containing outdated or unneeded chemicals is essential. 7)Installing high-efficiency particulate air (HEPA) filters and activated carbon filters in HVAC systems	7)[7]
Microbiological contaminants	1)Utilise a range of sampling methods. 2)Install gravity-based drop pans and ensure correct maintenance of non-steam humidifiers. 3)Implementing systematic cleaning routines with environmentally-friendly cleaning agents.	1)[2] 2)[2] 3)[8]
Particulate matter levels	1)Substituting the hazardous equipment with other gear or equipment that does not pose any risks. 2)The approach involves employing a general or local exhaust ventilation system. 3)The notion of local exhaust ventilation entails the deliberate and directed movement of air across a specific emission point to a system of ductwork. 4)Testers and teachers should receive training prior to using laboratory facilities. 5)Prior to utilising personal protective equipment (PPE). 6)The professors provide training to the pupils before to each experiment. 7)Warning signs were positioned at the laboratory entrance. 8)Attendants clean all laboratories on a weekly basis.	[33]

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3. Methodology

This flowchart facilitated the organization of the research process, starting from problem identification through identification of potential problems, bibliometric analysis, mitigation strategies identification, sampling methodology , data analysis and concluding with recommendations [16]. Phase 1 focused on identifying potential indoor air quality (IAQ) issues through an extensive literature review and bibliometric analysis, utilizing credible databases to examine key concerns in university laboratories. This phase established a foundation for understanding major IAQ challenges, including inadequate ventilation, chemical pollutants, microbiological contaminants, and particulate matter. In Phase 2, mitigation strategies were developed and evaluated based on findings from Phase 1. A structured survey was distributed to faculty members and staff responsible for laboratory management at Universiti Tun Hussein Onn Malaysia (UTHM) Pagoh to assess the effectiveness of various control measures. The collected data underwent statistical analysis, allowing for the prioritization of strategies such as optimizing ventilation systems, proper chemical waste disposal, and systematic cleaning protocols to improve IAQ management in university laboratories. By providing a clear representation of the study plan, the flowchart in the figure 1 below enabled researchers to align their analyses with the research goals of identifying potential sources of IAQ problems and corresponding mitigation strategies in university laboratories.

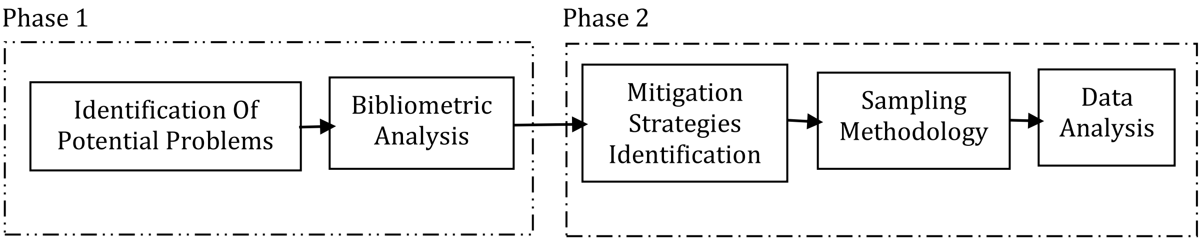

Fig. 1: Flowcart of methodology

3.1 Identification of Potential IAQ Problems

The identification of potential sources of IAQ problems commenced with a thorough literature review, focusing on recent studies published within six years prior to this research. Data was sourced exclusively from authorized databases at Universiti Tun Hussein Onn Malaysia (UTHM), which provided access to a range of scholarly articles relevant to IAQ issues in university laboratories [17]. The literature review was crucial for establishing a foundation for understanding current trends and challenges related to IAQ. All references were organized using Mendeley Desktop, which facilitated efficient management and retrieval of relevant literature, thereby enhancing the comprehensiveness of the bibliometric analysis conducted later in the study.

3.2 Bibliometric Analysis

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3.3 Mitigation Strategies Identification

A comprehensive list of mitigation strategies was developed based on identified potential sources of IAQ problems in university laboratories. This list included various physical parameters, chemical contaminants, and biological contaminants that could affect indoor air quality [19]. The strategies were summarized in a table format to facilitate easy distribution and understanding among participants during the questionnaire phase of the study. This systematic approach ensured that all potential issues were addressed comprehensively, providing a robust foundation for evaluating respondents' perceptions regarding effective mitigation measures.

3.4 Sampling Methodology

The study employed a cross-sectional design using stratified random sampling to select participants responsible for overseeing university laboratories. This method involved dividing the population into homogeneous strata based on demographic features such as roles and responsibilities [18]. The total population included 78 individuals from various roles within UTHM's Pagoh campus laboratories. Slovin's formula below was utilized to determine an appropriate sample size of 65 participants, ensuring that the sample accurately represented diverse perspectives within the laboratory environment [20]. This sampling strategy enhanced the reliability of findings by capturing a wide range of insights related to IAQ management.

$$\text{Slovin's formula}$$

$$n = \frac{N}{(1 + Ne^2)}$$

$$n = \frac{78}{(1 + 78(0.05^2))} = 65 \quad (1)$$

3.5 Questionnaire Instrumentation

A standardized questionnaire was developed based on insights gathered from the literature review regarding mitigation strategies for IAQ issues and bibliometric analysis. The questionnaire consisted of two parts: demographic information and evaluation of mitigation strategies using a 5-point Likert scale [21]. Table 2 shows the likert scale for questionnaire B. This structured approach allowed for efficient data collection over a four-week period while ensuring comprehensive participation from respondents. The use of Google Forms further emphasized efficiency and accessibility in disseminating the questionnaire.

Table 2: Likert scale for questionnaire part B

Answer	Scale
Strongly disagree with the mitigation strategies	1
Disagree with the mitigation strategies	2
Neutral with the mitigation strategies	3
Agree with the mitigation strategies	4
Strongly agree with the mitigation strategies	5

3.6 Data Analysis Techniques

Data analysis was conducted using various statistical methods to ensure robust findings. The Cronbach's Alpha test assessed internal consistency among questionnaire items, confirming the reliability of responses [22]. Descriptive statistics were employed to summarize data through mean scores and standard deviations for each mitigation strategy evaluated by respondents. Ranking analysis was conducted based on mean results to identify strategies perceived as most effective by participants.

4. Results and Discussion

This section presents the findings and analysis of the study on Indoor Air Quality (IAQ) Management and Mitigation Strategies in University Laboratories. The results are discussed systematically, linking the bibliometric analysis and questionnaire findings to address IAQ potential sources of problem and analysed mitigation strategies.

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4.1 Key Indicators of IAQ Potential Sources of Problem

Figure 2 shows the results of bibliometric analysis. The bibliometric analysis identified four primary IAQ indicators: physical parameters, chemical contaminants, biological contaminants, and particulate matter (PM) levels. Physical parameters, including inadequate ventilation, high temperature, relative humidity, and overcrowding, were found to exacerbate pollutant concentrations such as CO_2 and VOCs during academic hours in congested spaces [23]. Poor ventilation also leads to air stagnation, allowing pollutants like formaldehyde and carbon monoxide to accumulate [24]. Chemical contaminants such as NO_2, SO_2, and TVOCs were linked to improper waste management practices and photochemical reactions induced by sunlight entering through windows [25].

Biological contaminants included airborne microorganisms and fungal growth, with Staphylococcus species identified as a dominant bacterial genus linked to human activity in laboratories [26]. PM levels were influenced by overcrowding, poor infection prevention practices, and external pollution sources; high PM concentrations negatively impact respiratory health and cognitive performance [27]. While these findings highlight key IAQ challenges, the reliance on secondary data may limit their applicability to specific laboratory settings. Nevertheless, these results align with prior studies emphasizing the role of environmental controls in managing IAQ challenges [28][29]. Addressing these indicators can improve occupant health and productivity while ensuring compliance with environmental standards.

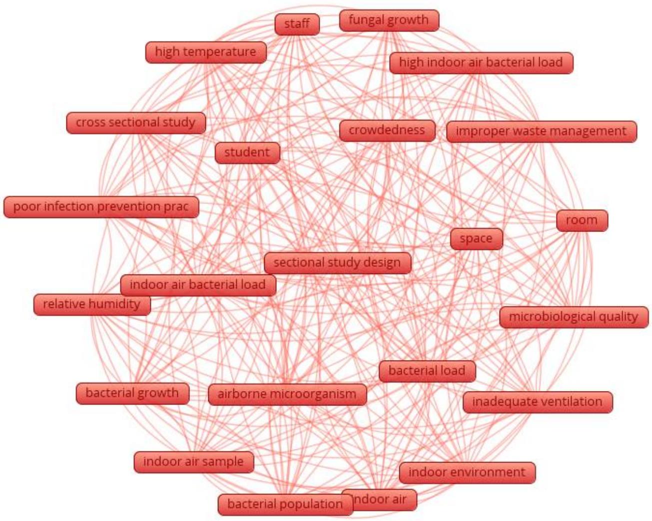

Fig. 2: Network visual of bibliometric analysis

4.2 Linked of Potential Sources of Problem and Mitigation Strategy

The study involved 69 respondents, exceeding the required sample size of 65 calculated using the Slovin formula. The questionnaire was distributed via Google Forms to staff and lecturers at Universiti Tun Hussein Onn Malaysia (UTHM) Pagoh, including those from Pejabat Pengurusan Makmal Kampus Cawangan Pagoh (PPMKCP) and the Civil and Chemical Engineering Technology sub-clusters. Of the respondents, 37 were female and 32 were male. The largest age group was 36–45 years (34 respondents), followed by 26–35 years (24 respondents), and 46 years and above (11 respondents). Lecturers constituted the majority (48), with 8 laboratory assistants and 4 coordinators. Regarding work experience, 34 respondents had 4–6 years of experience, 25 had over 7 years, 9 had 1–3 years, and 1 respondent had less than a year. These demographics served as a basis for analyzing mitigation measures to enhance indoor air quality in university laboratories. The reliability of the questionnaire survey in table 3 was evaluated using Cronbach's Alpha, with all categories scoring above 0.80, indicating strong internal consistency and the reliability of items for assessing IAQ management in university laboratories. The physical parameters category achieved the highest reliability at 0.889, highlighting the effectiveness of strategies like ventilation improvements and HVAC maintenance [41]. Chemical contaminants scored 0.849, validating measures such as HEPA filters and proper chemical disposal [42]. Biological contaminants scored 0.846, reflecting reliable mitigation approaches like cleaning routines and mold prevention [40] while PM levels scored 0.801, confirming the consistency of measures like local exhaust systems and staff training [43].

Table 3: Cronbach's Alpha test according to each potential sources problem

Mitigation strategies for the management of IAQ by each potential sources problem	Cronbach's Alpha
Inadequate air circulation and insufficient air supply	0.889
Chemical pollutants	0.849
Microbiological and biological contaminants	0.849
Particulate matter (PM) levels	0.801

4.2.1 Mitigation Strategies in Inadequate Air Circulation and Insufficient Air Supply

The mitigation strategies for indoor air quality (IAQ) management in university laboratories were derived from questionnaire survey ranking analysis and categorized into four IAQ indicators: inadequate air circulation, chemical pollutants, microbiological contaminants, and particulate matter (PM) levels. Fig 2 shows the linked potential sources of problem to the rank of mitigation strategies. For inadequate air circulation, maintaining air balance in ventilation systems (IA1) ranked highest (mean score: 4.72), as balanced systems significantly reduce pollutant concentrations through proper airflow control [30]. Routine duct cleaning (IA2) ranked second (mean score: 4.71), emphasizing its importance in preventing blockages that hinder airflow [31].

Establishing standard mechanical systems (IA3) ranked third (mean score: 4.59), supporting ventilation quality necessary for laboratory environments [32]. Filter replacement in HVAC systems (IA4) ranked fourth (mean score: 4.58), as clean filters prevent contamination caused by accumulated pollutants [33]. Mechanical ventilation to increase air quantity (IA5) ranked lowest due to its focus on volume rather than quality. Table 4 summarizes the mitigation strategies for inadequate air circulation.

Table 4: Mitigation strategies for inadequate air circulation

Item	Mitigation strategies for the management of IAQ by inadequate air circulation	Mean	Std Deviation	N	Rank
IA1	Performing air balance in the ventilation system.	4.72	0.539	69	1
IA2	Regular maintenance of ventilation systems by duct cleaning	4.71	0.517	69	2
IA3	Enhancing the quality of ventilation through mechanical ventilation.	4.59	0.602	69	3
IA4	Regular maintenance of ventilation systems by filter replacement.	4.58	0.715	69	4
IA5	Enhancing the quantity of ventilation through mechanical ventilation.	4.57	0.606	69	5

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4.2.2 Mitigation Strategies in Chemical Pollutants

For chemical pollutants, the proper disposal of outdated chemicals (CP1) ranked highest (mean score: 4.65), addressing risks of chemical infiltration into indoor air [34]. HEPA filtration in HVAC systems (CP2) ranked second (mean score: 4.59), praised for its efficiency in trapping airborne chemical particles [35]. Activated carbon filters (CP3) ranked third (mean score: 4.58), recognized for neutralizing volatile organic compounds common in laboratories. Systematic evaluation of indoor air quality (CP4) ranked fourth (mean score: 4.55), while periodic non-occupancy intervals (CP5) ranked lowest due to limited practicality despite its benefits in maintaining air quality during vacancy periods [36]. Table 5 summarizes the mitigation strategies for chemical pollutants.

Table 5: Mitigation strategies for chemical pollutants

Item	Mitigation strategies for the management of IAQ by chemical pollutants	Mean	Std Deviation	N	Rank
CP1	Proper disposal of outdated or unneeded chemicals	4.65	0.614	69	1
CP2	Installing high-efficiency particulate air (HEPA) filters in HVAC systems effectively	4.59	0.714	69	2
CP3	Installing activated carbon filters in HVAC systems effectively and volatile organic compounds (VOCs).	4.58	0.651	69	3
CP4	Continuous monitoring of indoor air quality.	4.55	0.777	69	4
CP5	Implementing periodic non-occupancy intervals and encouraging occupants to take breaks	4.28	0.873	69	5

4.2.3 Mitigation Strategies in Microbiological and Biological Contaminants

For microbiological contaminants, addressing moisture problems to prevent mold growth (BC1) ranked highest (mean score: 4.70), as moisture control is critical for reducing microbial proliferation and maintaining healthy indoor environments [37]. Dedicated facility cleaning using environmentally friendly agents (BC2) ranked second (mean score: 4.65), highlighting its effectiveness in minimizing biological contamination risks [38]. Introducing biotechnologies for pollution control (BC3) ranked third, emphasizing innovative solutions for improving IAQ. Laminar flow cabinets and fume hoods (BC4) ranked fourth, as they help reduce contamination during experiments [39]. Complete cleaning of laboratory equipment (BC5) ranked lowest, focusing on direct surface cleaning to reduce bio contaminants. Table 6 summarizes the mitigation strategies for microbiological contaminants.

Table 6: Mitigation strategies for microbiological contaminants

Item	Mitigation strategies for the management of IAQ by microbiological contaminants	Mean	Std Deviation	N	Rank
BC1	Regular clean of the laboratory environment with environmentally friendly agents.	4.70	0.494	69	1
BC2	Addressing moisture problems	4.65	0.538	69	2
BC3	Comprehensive sanitising and sterilisation of laboratory apparatus and utensils utilising	4.61	0.669	69	3

	particle-free water.				
BC4	Using laminar flow cabinets and fume hoods.	4.55	0.654	69	4
BC5	Using Biotechnologies to improve indoor air quality.	4.49	0.760	69	5

4.2.4 Mitigation Strategies in Indoor Air Particulate Matter (PM) Levels

For particulate matter levels, local exhaust ventilation systems (PM1) ranked highest (mean score: 4.77), demonstrating their ability to trap particulates at the source with over 90% efficiency in hazardous material processing environments [40]. Training staff and students on proper laboratory practices followed closely with a mean score of 4.67, emphasizing behavioral interventions to minimize PM generation. Warning signs promoting PPE compliance (PM3) ranked third due to their role in reducing exposure risks. Replacing dangerous tools with safer alternatives to prevent particle generation (PM4) ranked fourth, while weekly cleaning schedules for laboratories (PM5) ranked lowest due to their lower priority compared to direct PM control measures. While the ranking analysis reflects subjective perceptions of respondents within specific laboratory settings, it aligns with prior research advocating for engineering controls like local exhaust ventilation systems and HEPA filters as effective strategies for managing indoor air pollutants in laboratories and other high-risk environments [27][40]. These prioritized mitigation strategies provide actionable guidance for improving IAQ management practices in university laboratories by enhancing occupant health and safety while ensuring regulatory compliance. Table 7 summarizes the mitigation strategies for particulate matter levels.

***Table 7*:** Mitigation strategies for particulate matter levels

Item	Mitigation strategies for the management of IAQ by particulate matter levels	Mean	Std Deviation	N	Rank
PM1	Using local exhaust ventilation (LEV) systems to eliminate dust	4.77	0.458	69	1
PM2	Training staff and students on proper laboratory practices.	4.67	0.560	69	2
PM3	Warning signs at laboratory entrances improve compliance with personal protective equipment (PPE) requirements	4.59	0.577	69	3
PM4	Weekly cleaning of laboratories.	4.59	0.649	69	4
PM5	Substituting hazardous equipment with safer alternatives.	4.54	0.759	69	5

4.3 Discussion

Figure 3 shows mind map of the linked potential sources of problem to indoor air quality management with mitigation strategies for the indoor air quality management in university laboratories. Indoor air quality management in university laboratories was analyzed by ranking mitigation strategies across four key categories: inadequate air circulation, chemical pollutants, microbiological contaminants, and particulate matter (PM). For air circulation issues, balancing ventilation systems (IA1) ranked highest, demonstrating up to 85% pollutant reduction through effective air mixing and filtration [29]. Routine duct cleaning (IA2) improved efficiency and reduced contaminants [30]. Standard mechanical quality (IA3), filter replacement (IA4), and mechanical ventilation (IA5) followed in priority. The effective disposal of volatile chemicals (CP1) ranked top in managing chemical pollutants, as safer equipment replacement minimized hazards [33]. HEPA filtration (CP2) and activated carbon filters (CP3) followed, demonstrating efficiency in chemical trapping [34]. Air quality evaluation (CP4) and vacation ventilation (CP5) ranked lower.

The moisture control to prevent mold (BC1) was the highest strategy for biological contaminants [36]. Routine cleaning (BC2) and biotechnological air purification (BC3) were prioritized, while airflow systems (BC4) and equipment cleaning (BC5) were less impactful. For particulate matter, local exhaust systems (PM1) proved most effective, removing over 90% of pollutants [39]. Staff/student education (PM2), PPE compliance (PM3), safer tools (PM4), and weekly cleaning (PM5) completed the rankings. This study highlights the prioritized strategies' effectiveness in addressing specific indoor air quality challenges and achieving improved air quality in laboratory settings.

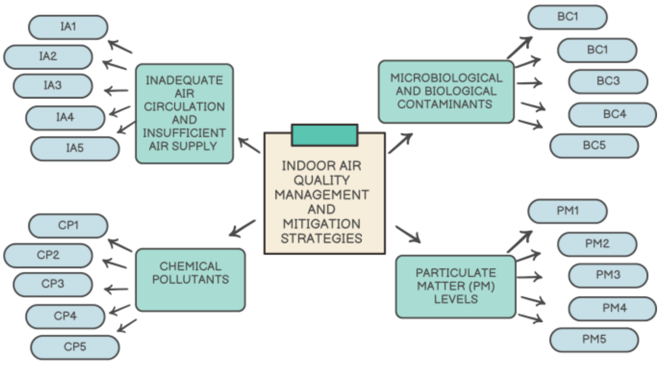

Fig. 3: Mind map of ranking analysis

5. Conclusion

This study focused on investigating indoor air quality (IAQ) management and mitigation strategies in university laboratories, employing a mixed-methods approach to address its two primary objectives. The bibliometric analysis conducted through VOSviewer software identified four main categories of IAQ concerns: inadequate air circulation and air supply, chemical pollutants, microbiological and biological contaminants, and particulate matter (PM) levels. Key sources of IAQ problems included factors such as inadequate ventilation, improper waste management, fungal growth, and high occupant density, highlighting the interdependent nature of these environmental challenges.

The findings demonstrated that balancing ventilation systems was the most effective measure for insufficient air circulation, while proper chemical disposal ranked highest for chemical pollutant management. Regular cleaning with environmentally friendly agents was identified as the top strategy for mitigating biological contaminants, and the use of local exhaust ventilation (LEV) systems proved most effective in controlling particulate matter.

These results underline the importance of systematic IAQ management tailored to specific challenges in laboratory settings. The study not only provides a comprehensive understanding of IAQ issues but also prioritizes actionable strategies that can enhance air quality in university laboratories. The insights gained offer a valuable foundation for developing evidence-based policies and practices to safeguard health and productivity in academic environments.

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