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Research Article

Assessing Indoor Environmental Quality (IEQ) Challenges in Autism Schools: Insights From Saudi Arabia's Eastern Region

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Saudi Arabia's Vision 2030 prioritises enhancing special education services for children with special needs, including autistic pupils who are particularly sensitive to their surrounding environment. Given that autistic pupils spend significant time in schools, Indoor Environmental Quality (IEQ) is critical for their well-being and learning outcomes yet remains underexplored. This study adopts a descriptive comparative design, using continuous monitoring and classroom activity observations to evaluate IEQ conditions in two autism schools in the Dammam region of Saudi Arabia during winter and summer. Measurements included air temperature, relative humidity, particulate matter ($PM_{2.5}$ and PM_{10}) concentrations, CO_2 levels, sound and lighting in classrooms. The IEQ parameters were measured using specific instruments installed at pupil level to accurately reflect their exposure. The findings reveal significant challenges in maintaining acceptable IEQ. $PM_{2.5}$ and PM_{10} concentrations exceeded WHO guidelines, with $PM_{2.5}$ averaging 51 $\mu g/m^3$ in School A and 30 $\mu g/m^3$ in School B. PM_{10} levels were even higher, peaking at 116 $\mu g/m^3$ in School A and 101 $\mu g/m^3$ in School B. These concentrations surpass those reported in mainstream schools in the same region, largely due to unique classroom activities (e.g., drawing, light physical activity) and cleaning practices (e.g., burning incense and use of sprays) prevalent in autism schools. Additionally, significant variations in lighting conditions highlight the need for adaptable systems to accommodate the sensory preferences and classroom activities of autistic pupils, which differ from mainstream students. These findings underscore the importance of addressing specific IEQ challenges in autism schools to improve pupil well-being and learning outcomes. This study advocates for the development of autism-friendly IEQ standards to guide future school design and operations.

Keywords: acoustics; air quality; autism; indoor environment; schools, Saudi Arabia; thermal

1. Introduction

Autism spectrum condition is recognised as a neurodevelopmental condition marked by challenges in social interaction and communication, as well as by restricted, repetitive behaviours and sensory reactivities [1]. This condition is acknowledged globally, with diverse approaches and resources from governments allocated to autism varying significantly across different countries and regions. Autism prevalence has been rising, with the World Health Organization (2023) reporting that approximately 1 in 100 children globally are diagnosed with the condition. In Saudi Arabia, the frequency rate rose to 2.5%, or 25 per 1000 children, from 2018 to 2019 [2]. The Saudi government has launched initiatives to establish specialised schools for autistic children. The Ministry of Human Resources and Social Development in 2021 provided a general specification for special needs schools. Despite these efforts to enhance educational

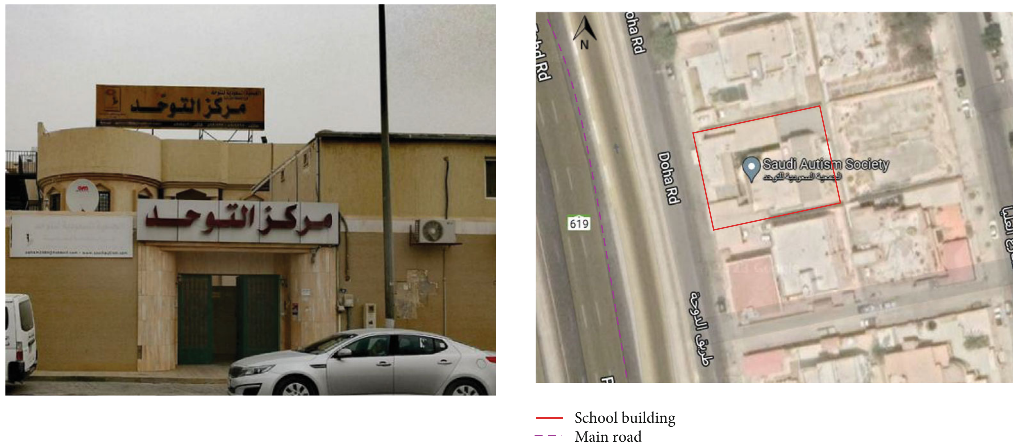
TABLE 1: Previous studies conducted in Saudi Arabia's schools.

Reference	Location	School	Parameter	IEQ assessment guideline	Result
[29]	Dammam	Elementary	Levels of PM_{10} and $PM_{2.5}$, volatile organic compounds, CO, NO_2 and CO_2	United States Environmental Protection Agency (USEPA 2006), the WHO, the National Institute for Occupational Safety and Health (NIOSH), the Occupational Health and Safety Administration (OSHA 1992), the American Conference of Governmental Industrial Hygienists (ACGIH 2001) and (ASHRAE 2010)	The pollution level exceeds the recommended standards. Schools located on busy streets have higher pollution levels than schools located on streets with low traffic activity. The air pollution level reduces with increasing the horizontal and vertical distances to the street. The ground floor shows a higher pollution level compared with the first floor.
[25]	Dammam	Elementary	Temperature, RH, air pollution (CO_2, CO,NO_2, SO_2 and TSP) and Benzene	WHO guidelines for air quality, EPA, NAAQS and OSHA	The pollution level was above the recommended standard. The level of pollution of classrooms located on moderate-traffic streets is higher. This result is due to mechanical ventilation.
[22]	Dammam	Primary	Ventilation rate and CO_2	ASHRAE 62 (2010) and WHO	Most of the schools had high CO_2 levels exceeding standards. In the renovated school, more than in governmental buildings, this indicates poor ventilation rates in classrooms.
(El-Sharkawy and Alsubaie [23])	Dammam	University	Noise level	WHO	The indoor and outdoor noise levels in the classroom are above the recommended level, which is caused by heavy traffic.
(Riham [24])	Jeddah	University	Temperature, RH and CO_2	—	The temperature and CO_2 had an impact on the pupil's cognitive performance depending on the task.
[27]	Jeddah		Dust-bound PAH levels	Environmental Protection Agency (EPA) of the United States	The high level of the PAHs source is related to vehicular traffic around the schools, which leaks to indoor classrooms.
[26]	Jeddah		Heavy metal partials		Schools located in urban areas show a higher level of heavy metals than those in suburban and residential areas. This is caused by high vehicular traffic emissions.
[28]	Jeddah		Temperature, RH, air velocity and global temperature	ASHRAE Standard 55-2010, Municipality of Dubai 2010	The air temperature in Jeddah schools is within standard during the use of air conditions in summer. Acceptability limits of male pupils are warmer than those of female pupils.

services for children with special needs, including those with autism, access to these institutions remains limited [3].

Autistic individuals often exhibit diverse sensory responses to their surroundings, including hyperreactivity (intense responses to stimuli), hyporeactivity (underresponses) and sensory-seeking behaviour (a desire for specific sensory experiences) (Lane et al. 2010; Brinkert and Remington 2020; [4]). Environmental stimuli frequently initiate significant stress for autistic individuals, particularly those related to sensory processing (Zaniboni et al. 2021). For example, hyperreactivity can make school environments with loud noises and intense visual stimuli overwhelming or intolerable for some autistic pupils (Elwin et al. 2013; Forsyth and Trevarrow 2018). Indoor environmental parameters such as acoustics, lighting and temperature can significantly influence the performance and learning experiences of autistic children in classroom ([5]; den Houting et al. 2018). Given these sensory sensitivities, understanding how IEQ parameters directly interact with the sensory needs of autistic pupils is critical for improving their educational environments.

Specialised schools for autistic children are designed to accommodate their unique needs, following specific guidelines that differ from those of mainstream schools. Emerging design recommendations, such as ASPECTSS [6] and the *Design Standard on Neurodiversity and the Built Environment* [7], focus on creating sensory-inclusive environments that address the specific educational requirements of autistic



(a) School A exterior and site plan

(b) School B exterior and site plan

Figure 1: School case studies in the Eastern Province, Saudi Arabia.

pupils. Key design considerations include sensory quality, intelligibility and the predictability of classroom spaces [8]. Educational programmes like TEACCH, designed to address developmental and sensory needs, offer targeted pedagogical support [9]. Autistic pupils frequently face challenges with communication and sensory processing, including hypersensitivity or hyposensitivity to stimuli such as light, sound and visual clutter [10].

Recent studies have highlighted strategies for accommodating autistic pupils, including zoning, spatial sequencing, thresholds, wayfinding, escape spaces, sensory rooms and controlling sensory stimuli like acoustics, lighting and colour [6, 11–14]. To address sensory sensitivities, specialised classrooms often feature sensory regulation mechanisms, such as sound-absorbing materials for acoustic control, quiet zones and optimised lighting through natural light and adjustable systems by avoiding fluorescent lighting [12]. These design features, tailored to autistic pupils' sensory processing needs, create distinct IEQ conditions that differ from those in mainstream schools. Understanding the relationship between IEQ and the physical design of these environments is crucial for improving the learning experiences of autistic pupils.

Although few experimental studies have investigated IEQ in autism-specific classrooms [15–18], existing research primarily focuses on acoustics and lighting [5, 19]. A comprehensive evaluation of IEQ parameters, including air quality, lighting and thermal conditions, is essential [20], especially since autistic pupils may experience the sensory environment differently [21]. Building this evidence base will facilitate the development of targeted adaptations that address the specific sensory sensitivities of autistic pupils, guiding which modifications should be prioritised to better support their needs.

Research on the IEQ of schools for autistic children, particularly in Saudi Arabia, is limited, with most studies focusing on mainstream schools. Approximately eight studies ([22–25]; Riham [24, 26–29]) examined air quality and thermal comfort, revealing that many classrooms exceed international standards for CO_2, $PM_{2.5}$ and PM_{10} (Table 1). Contributing factors include overcrowding, inadequate ventilation systems and the behavioural patterns of pupils. A global review shows significant variations in $PM_{2.5}$ and PM_{10} levels across elementary school classrooms, with Asia and Europe experiencing higher concentrations than other regions [30]. Additionally, a substantial percentage of classrooms do not meet the World Health Organization's standards for $PM_{2.5}$ ($5\,\mu g/m^3$) and PM_{10} ($15\,\mu g/m^3$) [31], particularly during the winter, indicating that indoor air quality in many schools may not meet health-based standards.

In Saudi Arabia, outdoor air quality is affected by dust storms, contributing to elevated levels of particulate matter (PM) [32]. Further studies in Dammam, located in the Eastern

TABLE 2: Architectural feature of classrooms.

Case	Date	General No.	Floor	Classroom Orientation	Area	Vo[1]	WA[2]	Window design NW[3]	WT[4]	Ventilation	MW[5]	Occupant number	Window shade
School A	12, 21 Dec 3, 4 Sep	A1	1	NE	24.5 m^2	73.5 m^3		3				6	
	13, 14 Dec	A2	1	SE	25 m^2	74.7 m^3		2				5	
	15, 20 Dec	A3	1	E	20 m^2	60 m^3	1.1 ∗ 2.2	1			1.1 m	5	Yes
	19 Dec	A4	1	SW	24 m^2	72 m^3		1				4	
	22, 25 Dec 5 Sep	A5	G	SW	24 m^2	72 m^3		1				7	
School B	27 Dec, 1, 3 Jan	B1	G	S				1				13	
	28, 29 Dec	B2	G	S				1	Manually, sliding	Single side	2.2 m	13	
	2, 4, 8 Jan	B3	G	S				1				8	
	9 Jan	B4	G	N				1				8	
	26, 30 July, 6 Aug	B5	G	N	42.5 m^2	127.5 m^3	3.4 ∗ 2.2	1				6	No
	9, 13 Aug	B6	G	N				1				6	
	7, 8 Aug	B7	1	S				1				5	
	31 July, 1, 2 Aug	B8	G	S				1				9	

Note: 1: Volume (Vo, m^3); 2: window area (WA, m^2); 3: number of windows (NW); 4: windows type (WT); 5: minimum height of window (MW, m).

Province, identify industrial and construction activities as significant contributors to poor air quality [33]. Elsharkawy et al. [29] examined 17 schools in Dammam during the COVID-19 pandemic, finding PM_{10} levels ranging from 12 to 29.3 $\mu g/m^3$, with approximately 82% of schools exceeding WHO's 2021 recommended threshold of 15 $\mu g/m^3$. Similarly, $PM_{2.5}$ levels in all schools studied surpassed the WHO recommendation of 5 $\mu g/m^3$. Indoor sources, such as the cultural practice of burning Arabian incense, further contribute to poor air quality, impacting health [34]. Indoor PM is considered the fifth most significant health risk factor in Saudi Arabia [35], underscoring the importance of maintaining proper IEQ in schools. Poor IEQ can have detrimental effects on children's development, particularly for those with special educational needs, such as autism [20, 36].

A notable research gap exists in the limited investigation of how IEQ parameters—air quality, temperature, acoustics and lighting—affect the wellbeing and educational outcomes of autistic children in Saudi Arabian schools. Although IEQ has been studied in general educational contexts, there is a lack of autism-specific research in the Middle East, where climatic, cultural and infrastructural conditions may alter both exposure and impact. This study evaluates IEQ conditions in two Saudi schools for autistic children, aimed at understanding how classroom environments influence learning and sensory comfort. The findings will inform evidence-based recommendations for autism-friendly design in regional schools, supporting improved educational outcomes and quality of life. These insights will also aid architects, engineers and researchers working on inclusive school design in comparable contexts.

2. Method

This section describes the investigated school buildings, the measurement protocols for the IEQ parameters and the IEQ guidelines applied to schools. The study adopts a descriptive comparative design, using continuous monitoring and classroom activity observations to analyse variations in indoor environmental quality across autism classrooms.

2.1. Site and Building Description. The IEQ was assessed in two specialised schools for autistic children, located in Dammam City on the Eastern Province of Saudi Arabia, the third-largest city in the country. The Eastern Province is characterised by hot and dusty environmental conditions, with an average annual temperature of approximately 27°C, peaking in July and August, and an average relative

TABLE 3: Instruments used for measurement of IEQ parameters.

Instrument	Indicators	Accuracy	Range	
Casella 62x digital sound level meter detector	Sound level with frequency analysis capability		20–140 dB	
Onset HOBO MX1102A bluetooth carbon dioxide, humidity and temperature data logger	CO_2 level temperature and RH	±50 ppm, ±0.21°C and 2% RH	0–5000 ppm, −20°C–70°C and 1%–90% RH	
Gossen M502B Mavolux 5032C digital footcandle and lux meter	Lighting level (Illumination level)	±3% ±1 digit	0.1–199,900 lux	
Gray wolf PC-3016A	$PM_{2.5}$, PM_{10} temperature and RH	8,000,000 particles/ ft^3	Counting efficiency: 50% for particles with 0.3 μm 100% for particles > 0.45 μm Uncertainty: 2.5% (10°C–40°C)/20%–95% RH	

humidity (RH) of 51% (Climate Data for Saudi Arabia 2022). Due to the extreme summer heat, air conditioning is extensively used, whereas buildings are naturally ventilated during the winter. Dammam City also has significant air pollution, primarily due to industrial activities and vehicular emissions, making it the city with the highest pollution levels in Saudi Arabia [33].

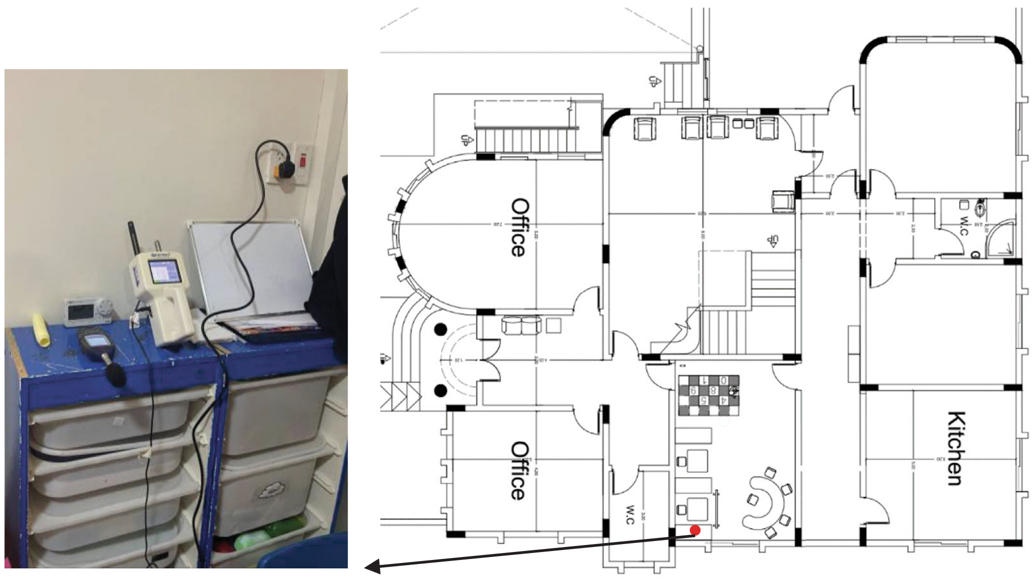
The two schools were selected for their educational and therapeutic focus on autistic children aged 4–12, with differing locations, construction ages and building standards that could influence IEQ (Figure 1). The variations between these two schools may impact IEQ conditions, making a comparative analysis critical for identifying potential design improvements:

- School A, established in 2010 in Dhahran, occupies a residential building renovated to serve the needs of autistic children. It is located close to a highway, which may be impacted by outdoor traffic emissions.

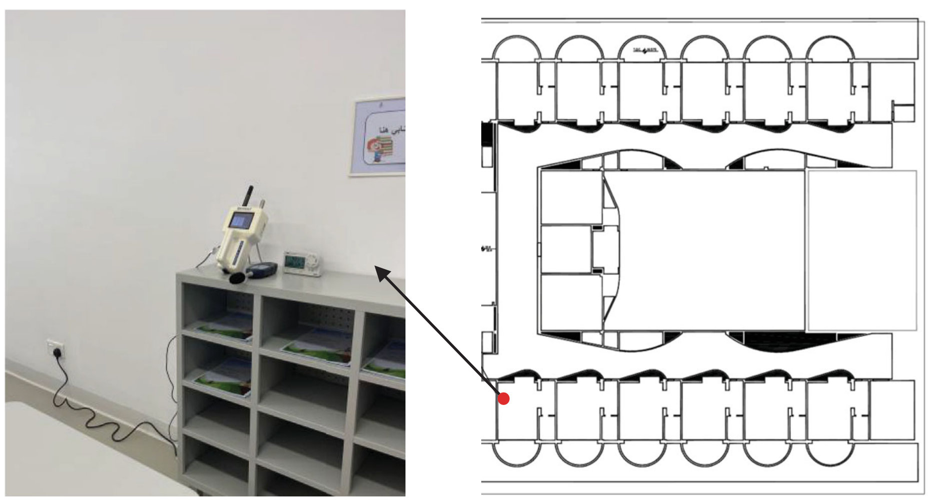
- School B, located in Al-Khobar and inaugurated in 2019, was designed by Simon Humphreys, an expert in creating spaces tailored for autistic individuals. This school adheres to National Autistic Society (NAS) standards, featuring a simple and clear environment for pupils. Its location near a park likely reduces its exposure to outdoor pollution.

2.2. Measurement. Two methods were utilised in the investigation: IEQ monitoring and the observation of pupil activity. Data were collected daily during the winter months of December 2022 and January 2023, when the buildings operated in free-running mode, and in the summer months from July to September 2023, when air-conditioning systems were active. Winter and summer were selected to represent the seasonal extremes in local climatic conditions, enabling comparison of indoor environmental quality under contrasting thermal contexts.

IEQ parameters and activity observation were measured in 13 classrooms, with one classroom monitored per day during standard school day hours (7 a.m.–12 p.m.), ensuring consistency in daily cleaning protocols and ventilation methods to prevent interference with the data (Table 2). The sample size reflected the total number of autism-specific classrooms accessible during the study period. All classroom occupants, including pupils, teachers and data collectors, were present throughout the measurement period.



(a) Instruments' location in Classroom A5 at School A



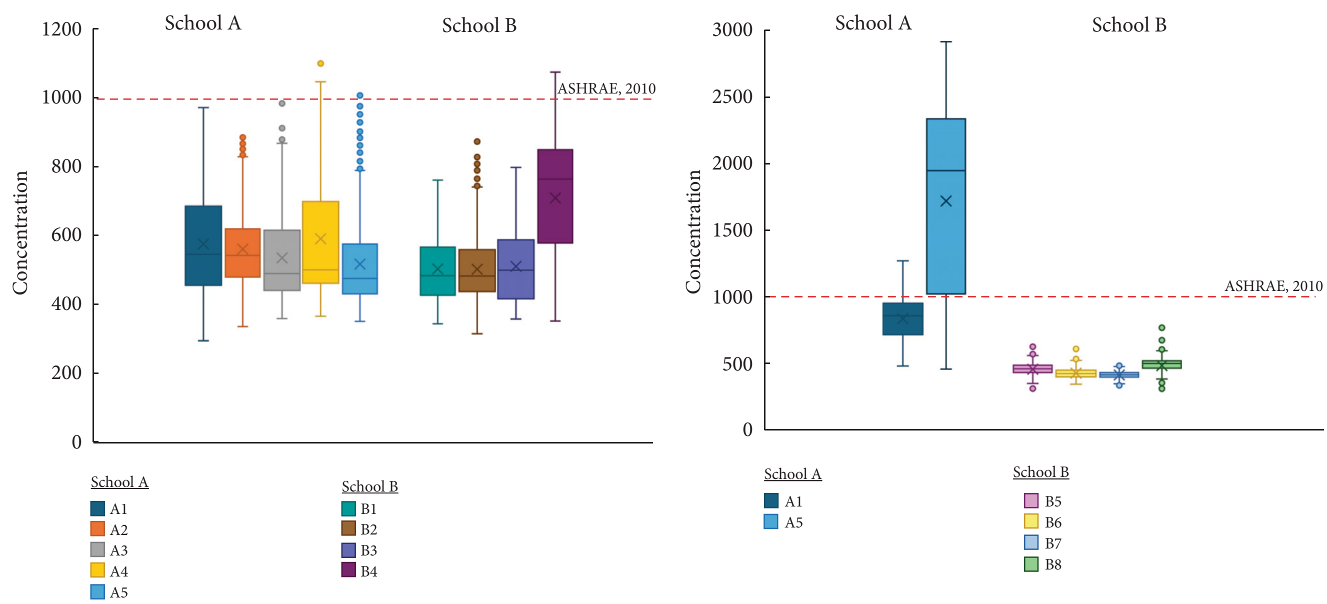
(b) Instruments' location in Classroom B1 at School B

Figure 2: The instruments' setup location in schools.

TABLE 4: Recommend guidelines for IEQ in schools.

IEQ	Recommended values	Standards/references
CO_2 concentration	< 1000 ppm	(ASHRAE 2010)
$PM_{2.5}$ concentration	$5\ \mu g/m^3$	(WHO 2021)
PM_{10} concentration	$15\ \mu g/m^3$	(WHO 2021)
Air temperature (natural ventilation)	$T_{com} = 0.25T_{rm} + 19.14$ T_{com} mean comfort temperature T_{rm} running mean outdoor temperature	[41]
Air temperature (mechanical ventilation)	23°C–25°C	Saudi Energy Efficiency Center (SEEC 2015)
Relevant humidity	40%–75%	(BB101 2018)
Sound level	*Background noise* [a] < 35 dB *Sound level* > 70 dB	[42]
Lighting level	300 lux	(IESNA 2003)

[a]Background when the classroom is not occupied.



(a) During winter

(b) During summer

FIGURE 3: Boxplot of CO_2 concentration in the two studied schools.

2.2.1. IEQ monitoring. Subjective assessments dominated the reviewed studies, especially in lighting (e.g., Gaines et al. 2014), creating variability. Recognising that autistic individuals often perceive stimuli more intensely [4], we adopted objective measurements to improve accuracy. Studies on nonautistic children ([37, 38]; Turunen et al. 2014) and recent autism-specific findings ([39]; Zaniboni and Toftum 2023) supported our focus on quantifiable data, particularly in underexplored domains like air quality.

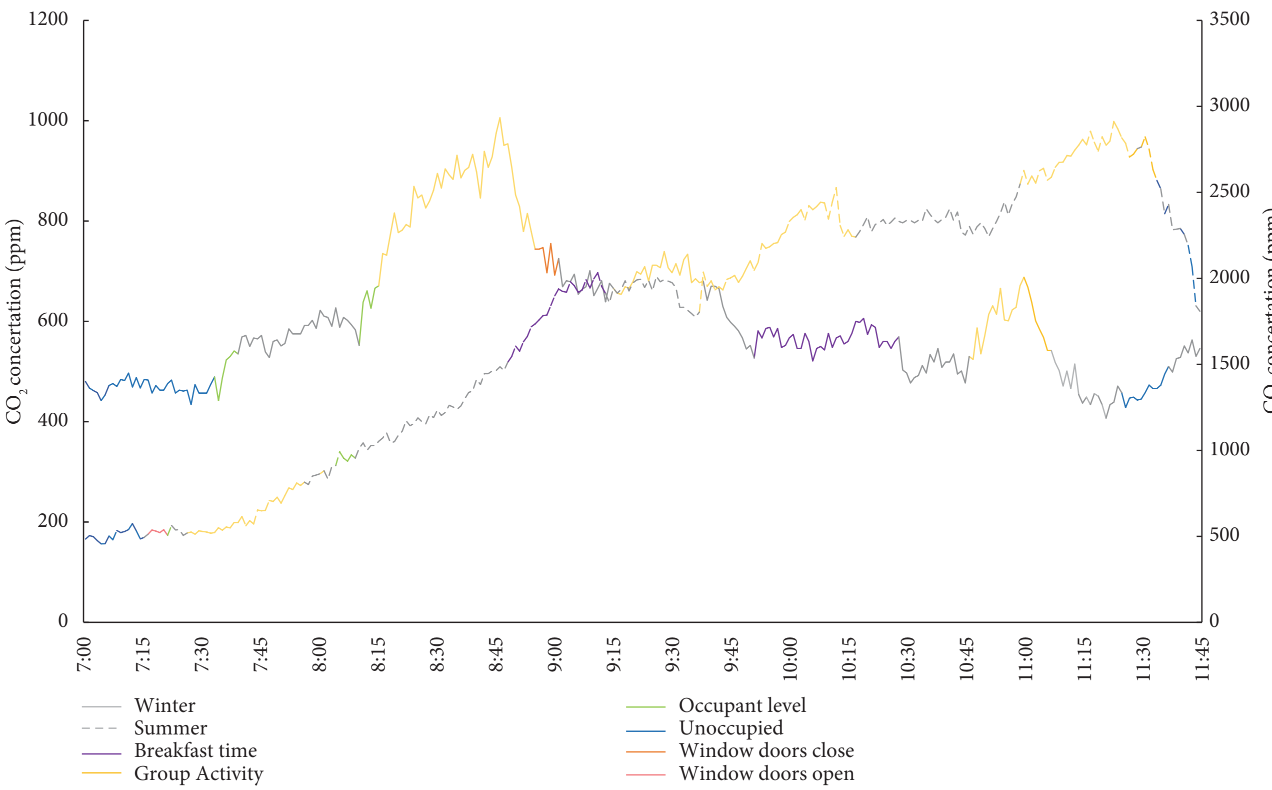
The IEQ parameters measured in classrooms included sound levels indicating acoustical comfort, lighting levels (illuminance) indicating visual comfort, air temperature, RH impacting thermal comfort, CO_2 concentration and $PM_{2.5}$ and PM_{10} concentrations indicating healthy air quality (Table 3). To ensure the accuracy and reliability of the data, measurements were taken at 1-min intervals throughout the study period. Instruments were positioned at a height of 0.85 m from the floor, corresponding to the typical seating level of pupils, to capture environmental conditions reflective of their actual exposure (Figure 2). The measurement protocol began at 7:00 a.m. and continued for 1 h after the school's closing time, providing a comprehensive overview of the environmental conditions encountered by pupils during the typical school day. Sound levels, air quality and thermal conditions were measured continuously, whereas lighting levels were assessed at three points in the classroom (front, middle and back) at three different times: the beginning of the class, just before the lunch break and at the end of the school day.

Fixed, in-situ sensors were used for continuous monitoring of indoor environmental parameters, providing precise, high-resolution data at the classroom level. This validated approach ensured reliable microscale measurements suited to occupied learning spaces. The integration of sensor data through centralised networks, as demonstrated in other environmental monitoring systems, supports real-time analysis and reinforces the methodological reliability of this study's measurement framework ([40]; Viani 2024).

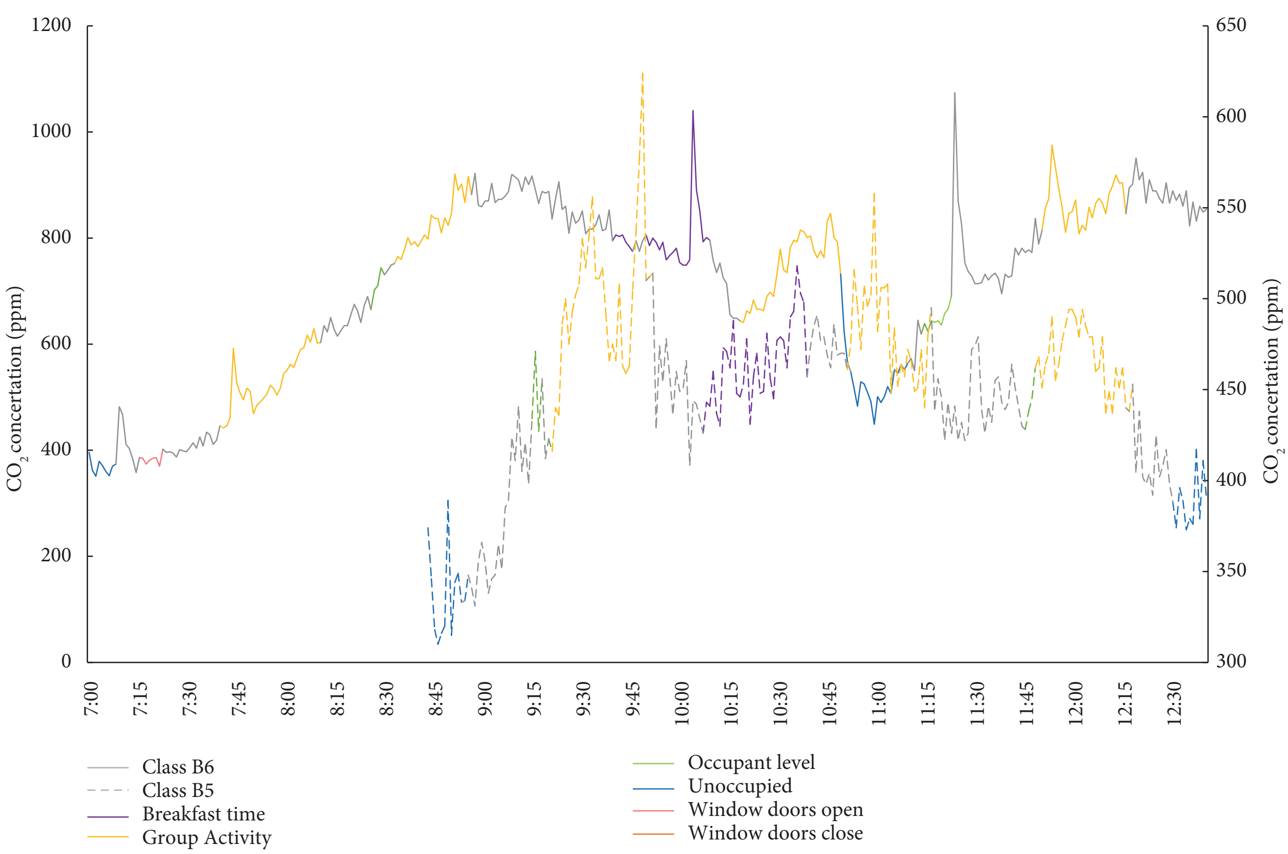
2.2.2. Outdoor Measurement. Outdoor environmental data were collected from nearby weather monitoring stations, including dry-bulb temperature, RH, $PM_{2.5}$ and PM_{10} levels during the study period. Dry-bulb temperature and RH data were sourced from the hourly climate integrated surface data (National Oceanic and Atmospheric Administration, Saudi Arabia) for the periods between December 1, 2022, and January 31, 2023, as well as July 1 to September 30, 2023. Outdoor PM data were obtained from the Al-Khobar station in the Al-Khobar Governorate, Eastern Province (World Air Quality Index Project); however, PM data were only available for December 2022 and January 2023.

2.2.3. Activity Observation. The types of activities, occupancy levels and the operational status of windows and doors (whether open or closed) within the classroom were closely monitored. Pupils participated in various activities throughout the day, including music, cleaning and other tasks, all of which could impact the IEQ conditions. Observations were recorded every 15 min to ensure consistent monitoring of these factors (Figure A1).

2.2.4. IEQ Standard. The study compares IEQ parameters in autism classrooms with existing standards for mainstream educational buildings, as specific guidelines for autism classrooms are not yet available. Relevant factors such as geography and pupil age were considered. Table 4 outlines the IEQ

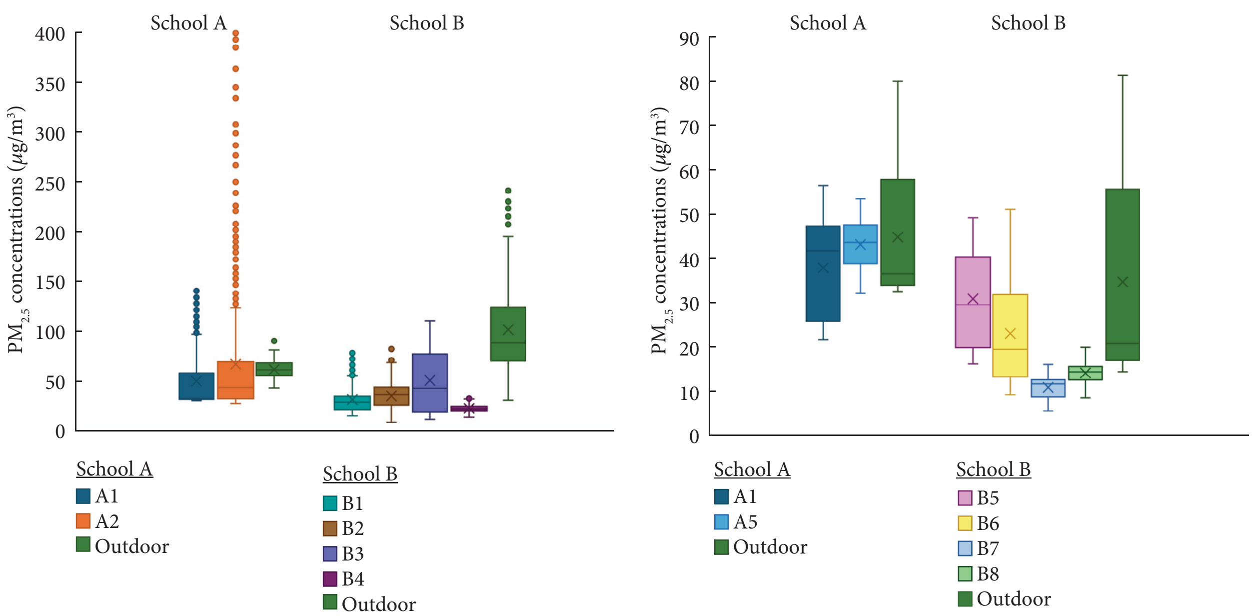


(a) CO_2 level profile in Classroom A3 in School A during winter and summer



(b) CO_2 level profile in Classrooms B4 and B5 in School B during winter and summer

FIGURE 4: CO_2 concentration daily profile in two schools.



(a) During winter

(b) During summer

FIGURE 5: Boxplot of $PM_{2.5}$ concentration in the two studied schools.

recommendations for mainstream schools, and the study's findings were assessed against these benchmarks.

2.3. Ethical Considerations. Ethical approval for this study was obtained from the University of Reading. Permissions were secured from participating schools prior to data collection. No personal or behavioural data were collected from pupils; observations focused solely on classroom environmental conditions and activity patterns.

3. Results and Discussion

3.1. Air Quality

3.1.1. CO_2 Concentration. As shown in Figure 3, 37% of summer-monitored data in School A exceeded the 1000 ppm threshold, whereas only 0.4% of winter-measured data surpassed this level. The average CO_2 levels in School A ranged from 834 to 1718 ppm in summer and 534 to 590 ppm in winter. In contrast, School B consistently maintained CO_2 levels below 1000 ppm during summer, with only 0.1% of winter recordings exceeding this threshold. The average CO_2 levels in School B ranged between 412 and 482 ppm in summer and 489 to 708 ppm in winter.

The elevated CO_2 levels in School A during summer are likely due to smaller classroom sizes (60–74 m^3) housing an average of seven occupants, compared with School B's larger classrooms (127.5 m^3) with eight occupants. Proximity to high-traffic roads may also contribute, as external CO_2 sources can influence indoor concentrations [43]. High CO_2 concentrations in classrooms like A5 raise concerns about ventilation suitability (Figure 4a). Mainstream schools often struggle with elevated CO_2 levels due to the low natural ventilation and high occupancy [25, 29].

In autism classrooms, the need for secure environments to prevent escape behaviours can limit natural ventilation, as operable windows and doors are often restricted for safety. Escape or avoidance behaviours, common in autistic individuals, are frequently triggered by overwhelming sensory environments, resulting in significant stress [44]. This was evident in Classroom B4 at School B, where CO_2 levels were elevated in winter due to prioritising safety over ventilation through closed windows and doors (Figure 4b). This reflects the challenge of maintaining indoor air quality while ensuring pupil safety.

The analysis also revealed variations in CO_2 levels based on different classroom activities. Studies have shown that CO_2 production increases with physical activity [45]. Significant fluctuations were observed during group activities, such as drawing and lunchtime (yellow line), where CO_2 levels appeared significantly higher compared with unoccupied classrooms (blue line), which showed minimal increases. Expected increases in CO_2 levels due to closed windows (pink line) and increased occupancy (green line) did not significantly manifest.

Although the CO_2 concentrations were within WHO and ASHRAE recommended levels, elevated levels during specific periods may still affect autistic pupils, who are sensitive to environmental changes. Research has shown that even modest increases—from 600 to 1000 ppm—can impair cognitive performance in nonautistic individuals [38]. These findings highlight the importance of maintaining stable environmental conditions in classrooms, especially for autistic children who may not fully understand the potential dangers [46].

3.1.2. $PM_{2.5}$ and PM_{10} Levels. The $PM_{2.5}$ and PM_{10} concentrations in both schools consistently exceeded WHO-

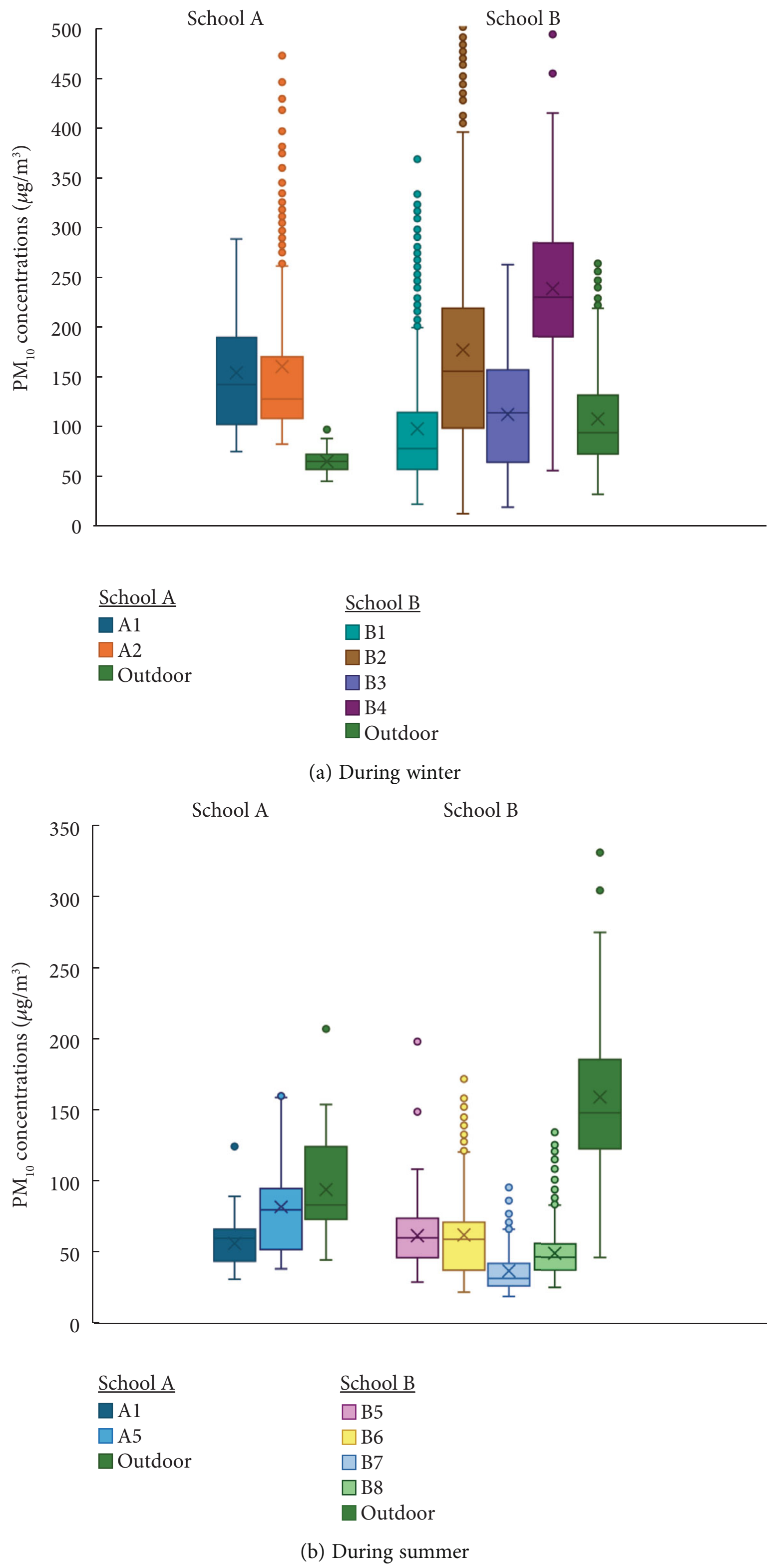
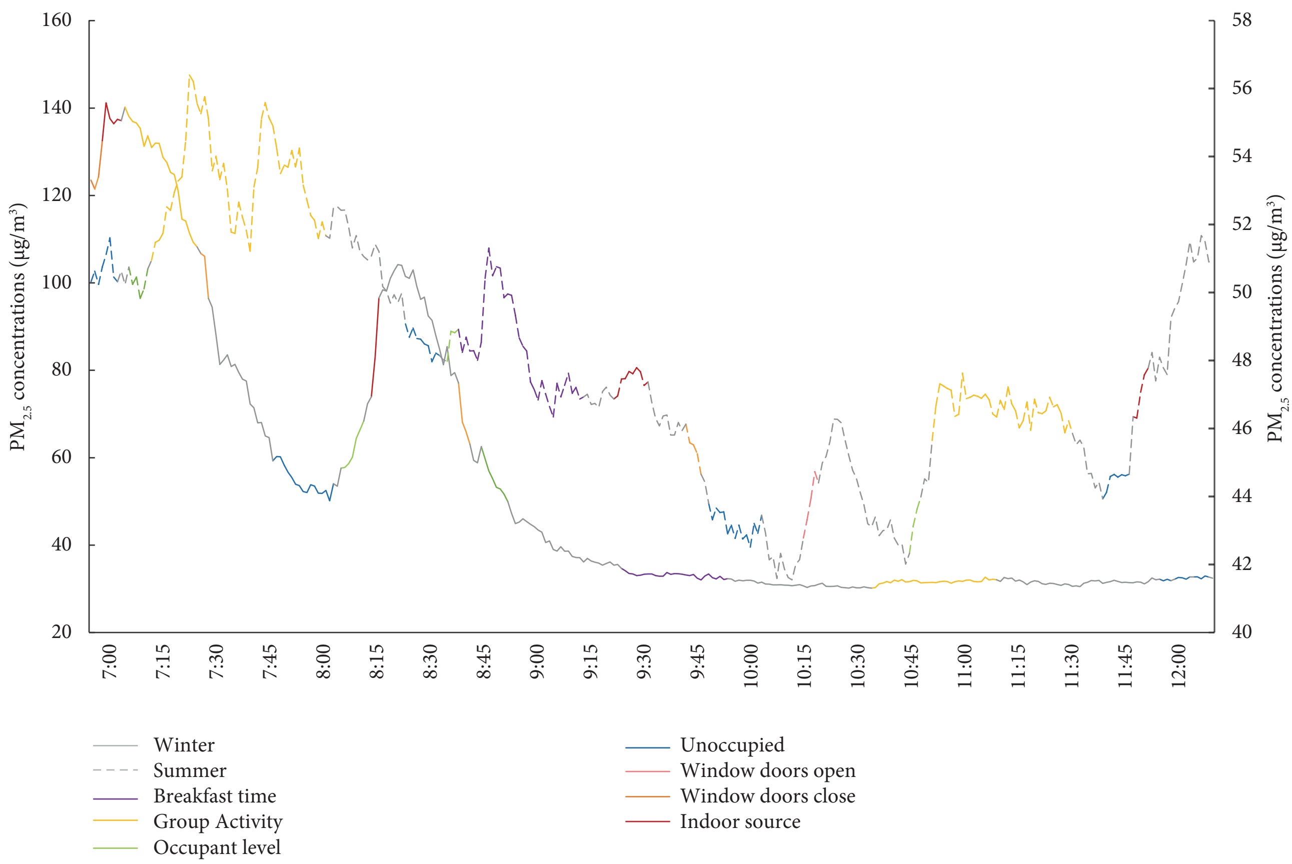


FIGURE 6: Boxplot of PM_{10} concentration in the two studied schools.

recommended thresholds (5 $\mu g/m^3$ for $PM_{2.5}$ and 15 $\mu g/m^3$ for PM_{10}), particularly during the winter [31]. In School A, $PM_{2.5}$ levels ranged from 49 to 66 $\mu g/m^3$ in winter and from 21 to 56 $\mu g/m^3$ in summer. School B recorded $PM_{2.5}$ levels between 22 and 57 $\mu g/m^3$in winter and 10–51 $\mu g/m^3$ in summer. PM_{10} levels followed a similar trend, with School A

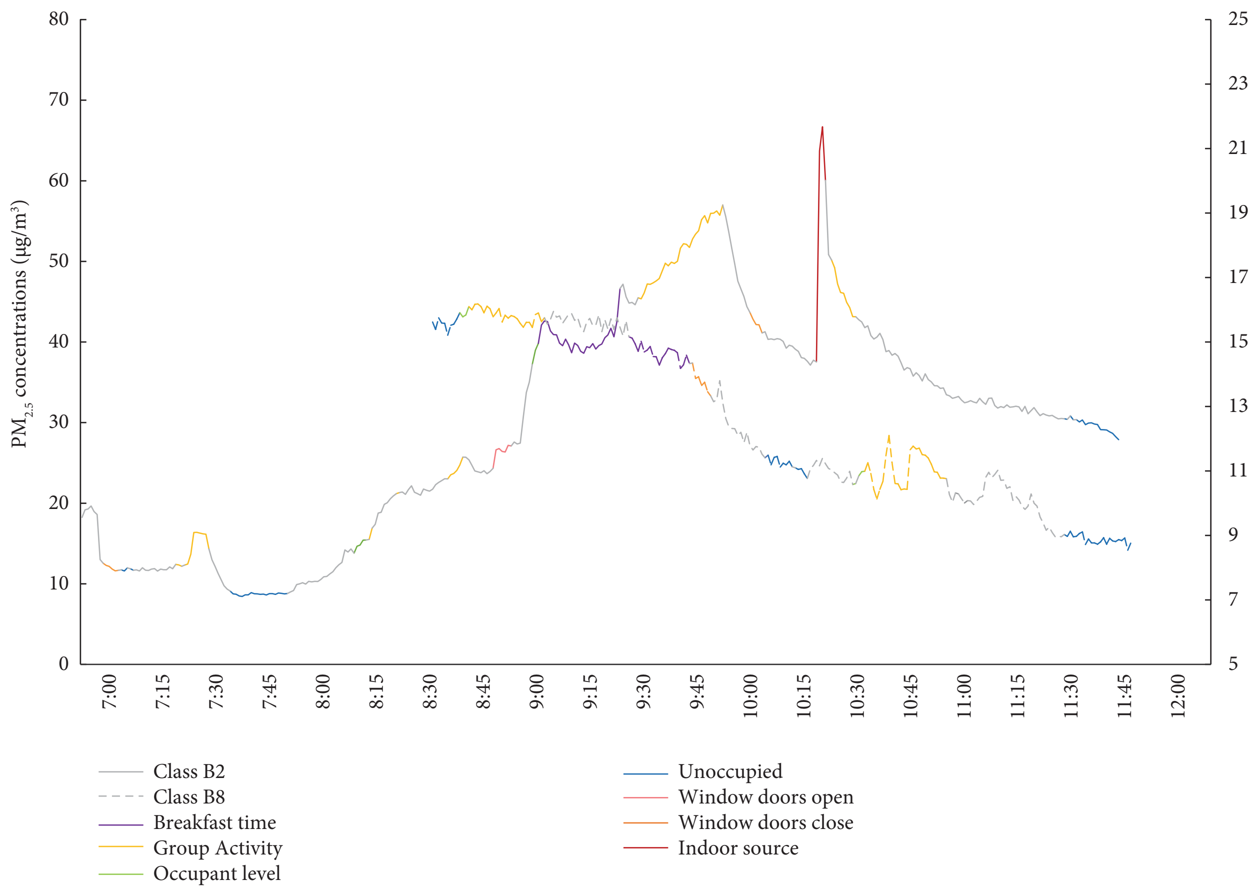
TABLE 5: I/O ratios for PM_{10}: mean values observed in each studied site for a day in the classroom.

School	Classroom	Winter			Summer		
		Indoor PM_{10} ($\mu g/m^3$)	Outdoor PM_{10} ($\mu g/m^3$)	I/O ratio	Indoor PM_{10} ($\mu g/m^3$)	Outdoor PM_{10} ($\mu g/m^3$)	I/O ratio
A	A1	154.1	63.9	2.4	60.2	113.3	0.5
	A2	160.2	63.9	2.5	—	—	—
	A5	77.3	50	1.5	81.6	62.8	1.3
B	B1	97.8	127	0.7	—	—	—
	B2	176.7	99.7	1.7	—	—	—
	B3	112.1	186.4	0.6	—	—	—
	B4	238.7	75.67	3.1	—	—	—
	B5	—	—	—	61.6	141.1	0.4
	B6	—	—	—	61.7	191.4	0.3
	B7	—	—	—	36.7	145.8	0.2
	B8	—	—	—	49.3	161.1	0.3



(a) $PM_{2.5}$ level profile in Classroom A1 in School A during winter and summer

Figure 7: Continued.



(b) $PM_{2.5}$ level profile in Classrooms B2 and B8 in School B during winter and summer

FIGURE 7: $PM_{2.5}$ concentration profile in two schools.

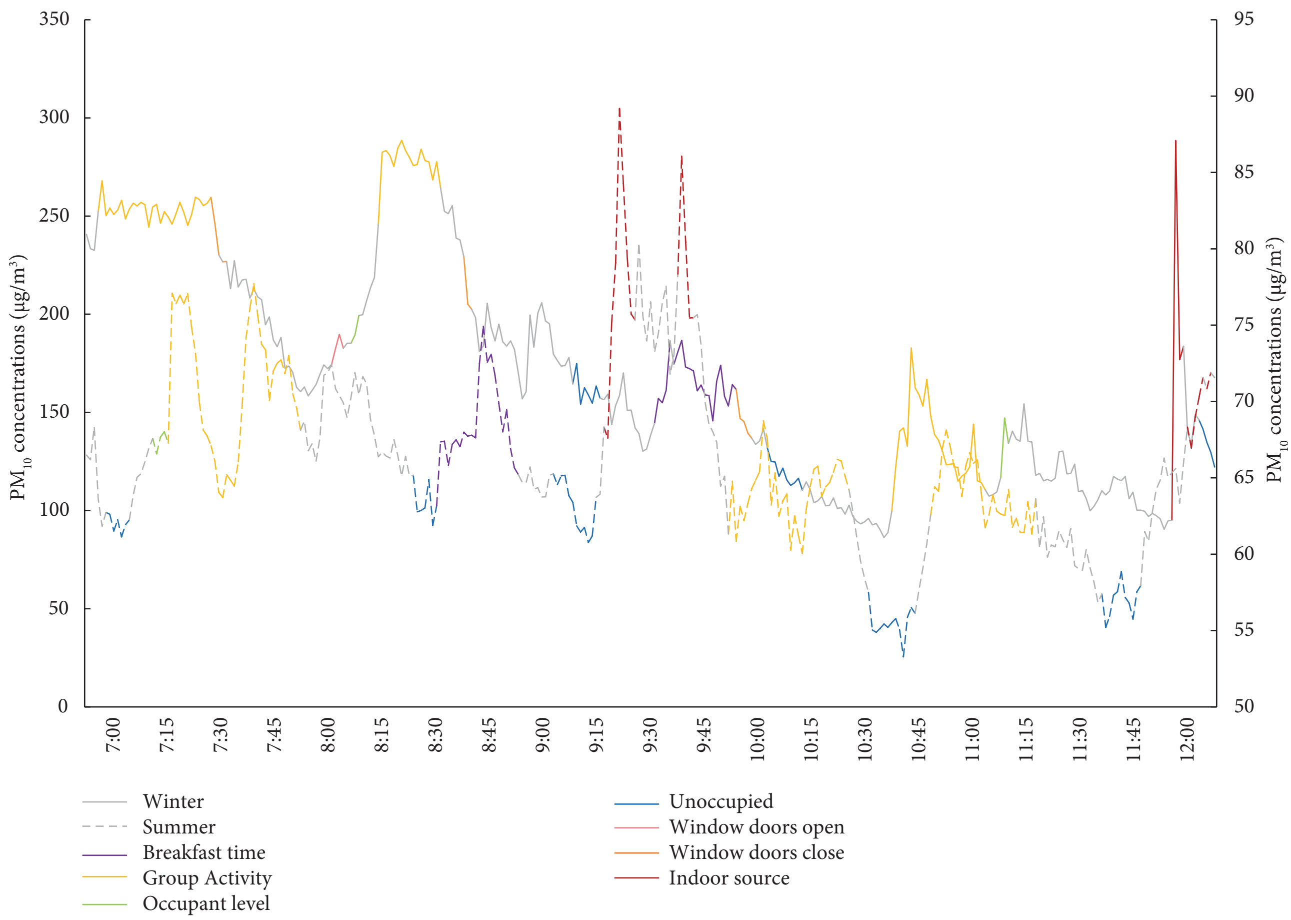
recording 49–160 $\mu g/m^3$ in winter and 55 to 81 $\mu g/m^3$ in summer. School B exhibited higher winter levels of 86–238 $\mu g/m^3$, than summer levels of 36–61 $\mu g/m^3$. This seasonal variation reflects increased outdoor pollution and lower ventilation rates during winter (Figures 5 and 6).

During winter, $PM_{2.5}$ levels were 38% higher in School A and 197% higher in School B compared with summer; PM_{10} levels were 23% and 32% higher, respectively. These patterns align with the Middle East research showing winter PM levels in classrooms up to 2.5 times higher than in other seasons [47]. The higher winter PM concentrations can be attributed to lower temperatures, higher RH and increased vehicle emissions [47–49]. Natural ventilation, the primary strategy during winter, allows outdoor pollutants to infiltrate classrooms, leading to PM_{10} levels above recommended limits, as observed in School A's Classroom 4 (Figure 5a).

Variations in PM concentrations across different classroom floors revealed that ground-floor classrooms consistently experienced higher PM levels than those on upper floors, consistent with regional studies [29, 47]. Classroom A4 in School A, for example, exhibited PM_{10} levels above recommended limits due to reliance on natural ventilation during winter (Figure 5a). This reflects the strong influence of outdoor pollution on indoor PM concentrations [47, 50]. Table 5 illustrates indoor-to-outdoor (I/O) ratios, with winter values in some classrooms exceeding 2.5, confirming pollutant infiltration despite ventilation.

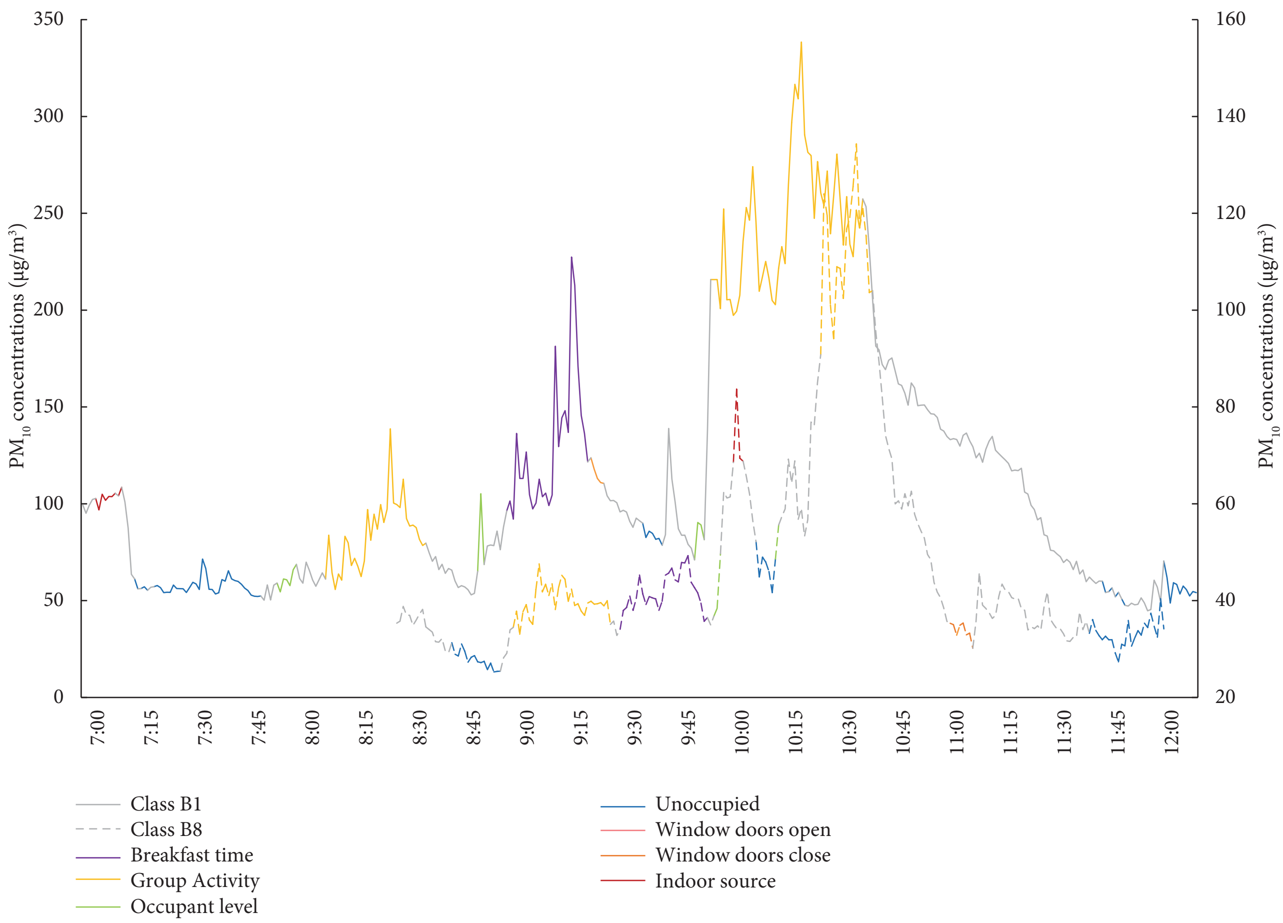
The profiles of $PM_{2.5}$ and PM_{10} concentrations in the classrooms (Figures 7 and 8) reveal multiple indoor sources contributing to levels exceeding WHO recommended values [31]. Indoor activities emerged as significant contributors to PM levels, particularly during periods of high occupancy and group activities. For instance, in Classroom A1 of School A, $PM_{2.5}$ and PM_{10} levels increased sharply during group activities like drawing or lunchtime (Figures 7 and 8). This aligns with Hama et al. [51], who reported a 230% increase in PM_{10} levels during high-occupancy periods in mainstream classrooms. Despite smaller class sizes (5–10 pupils) compared with mainstream schools, these activities substantially impacted air quality.

Physical activities further contributed to elevated PM levels, generating more airborne particulates than sitting activities. Alshitawi and Awbi [52] found that PM_{10} levels were 97 $\mu g/m^3$ higher during walking compared with 52 $\mu g/m^3$ when pupils were seated in the classroom. This trend was reflected in the study's classrooms, where PM levels varied significantly based on activity type and intensity.



(a) PM_{10} level profile in Classroom A1 in School A during winter and summer

Figure 8: Continued.



(b) PM_{10} level profile in Classrooms B1 and B8 in School B during winter and summer

FIGURE 8: PM_{10} concentration profile in two schools.

3.1.2.1. Indoor Sources of Pollution. Specific indoor sources led to intense PM spikes; for example, during incense-burning in Classroom A1 of School A, $PM_{2.5}$ concentrations reached 135 $\mu g/m^3$, and PM_{10} levels soared to 300 $\mu g/m^3$, far exceeding WHO recommendations. Similar increases were observed in School B due to cleaning spray usage (Figure 7). These findings confirm studies in mainstream schools in Qatar, where practices such as incense-burning elevated indoor $PM_{2.5}$ levels to $93.2 \pm 42.4\ \mu g/m^3$ and PM_{10} levels to $60.1 \pm 28.8\ \mu g/m^3$ [53]. Although incense burning, a common practice in Saudi schools, is used to create a pleasant atmosphere and mask odours (Amoatey et al. 2018; Cohen et al. 2013), it is a major contributor to indoor air pollution, as incense smoke contains chemical compounds with known health risks [54].

The higher PM levels in autism-specific classrooms can be partly explained by their unique operational characteristics. Teaching methods often involve frequent activities and breaks to help autistic pupils maintain focus and reduce distractions [55]. Moreover, some autistic pupils engage in sensory-seeking behaviours, such as touching or exploring textures, which can lead to messy environments [56]. Consequently, the need for frequent cleaning may account for the heightened use of cleaning sprays and other indoor pollutants.

Maintaining hygiene is especially critical in autism-specific classrooms, given sensory issues and challenges with self-care routines [57]. However, this emphasis on cleanliness often increases the use of cleaning agents and scented products like incense, inadvertently elevating $PM_{2.5}$ and PM_{10} concentration levels. Such exposure can negatively affect the pupils' health, attention and cognitive performance, with studies highlighting a correlation between elevated PM levels and adverse cognitive outcomes [58, 59]. For instance, the chemical compounds in incense smoke, such as p-Xylene and styrene, can impair cognitive functions with prolonged exposure [60].

Autistic individuals' sensitivity to strong smells and environmental changes compounds the issue, as incense and other strong-scented products may trigger anxiety and physical discomfort [4]. Thus, managing air quality in autism-specific classrooms is essential for creating a comfortable and supportive learning environment. However, limited research exists on the direct impact of air quality on the learning experiences of

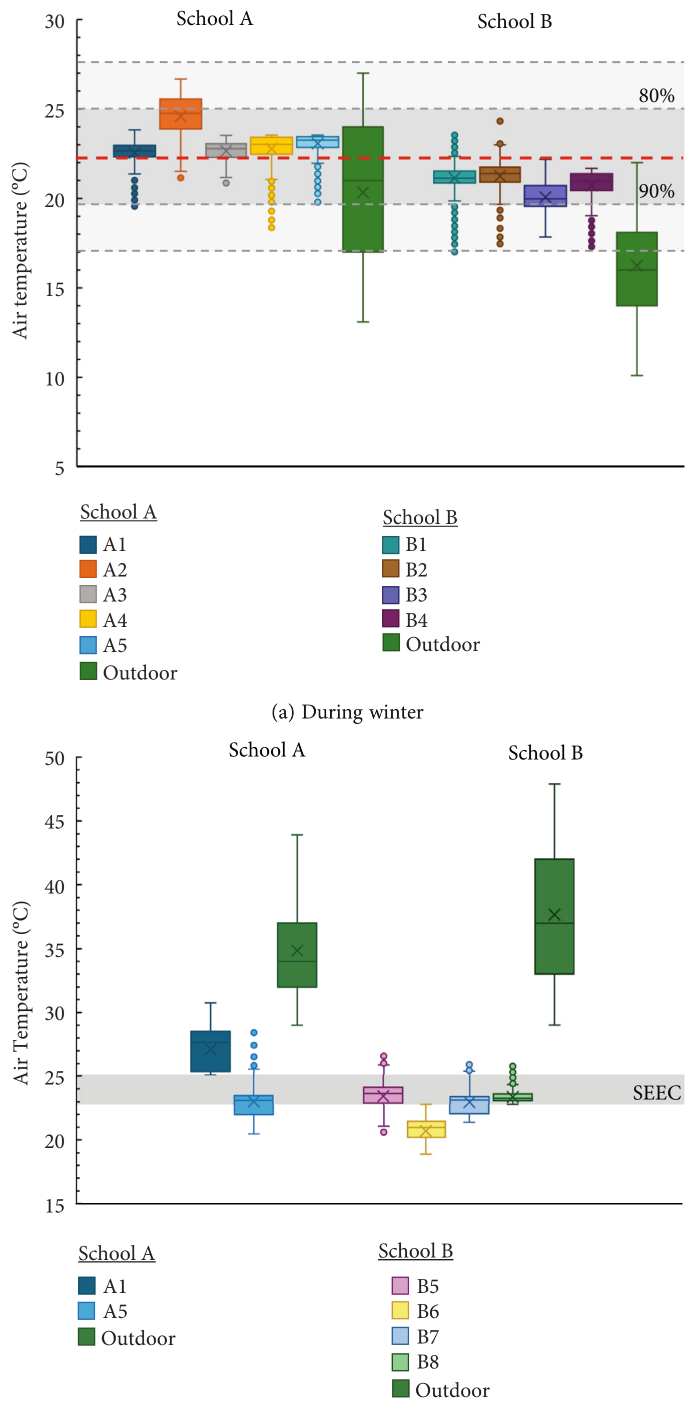
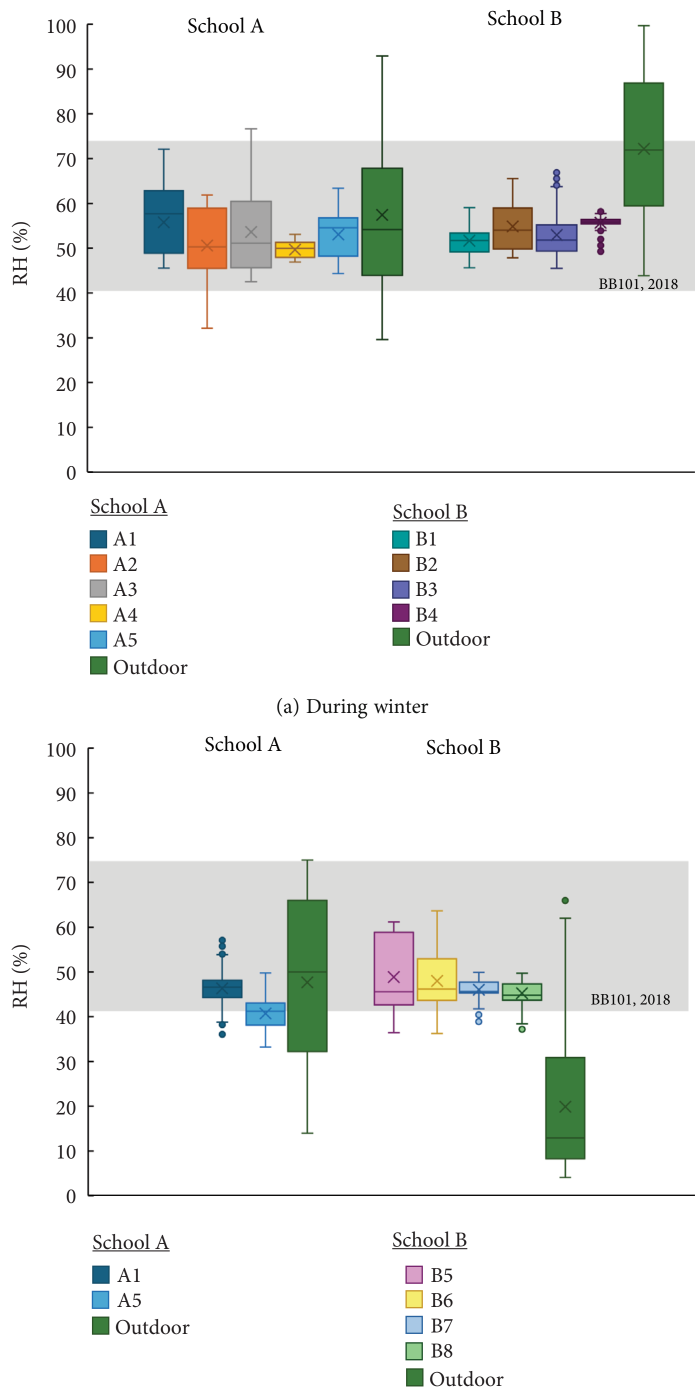


FIGURE 9: Boxplot of air temperature in two schools.

autistic pupils [5]. This gap underscores the need for further studies to explore how air quality influences cognitive and behavioural outcomes in autistic pupils, fostering strategies to optimise their learning environments.

Installing air filtration units (AFUs) is a common way to improve indoor air quality in schools. Studies show that AFUs effectively reduce PM exposure (van der Zee et al. 2017; Tong et al. 2020; Dai and Zhao 2022; Jiang et al. 2023). For example, Jiang et al. (2023) found that $PM_{2.5}$ concentration was significantly reduced to $20 \pm 2\,\mu g/m^3$ after 40 min, whereas outdoor concentration was about 114 ± 13 $\mu g/m^3$. Improved air quality enhances pupils' learning progress and may improve the sensory experience of autistic pupils (Xu et al. 2023).



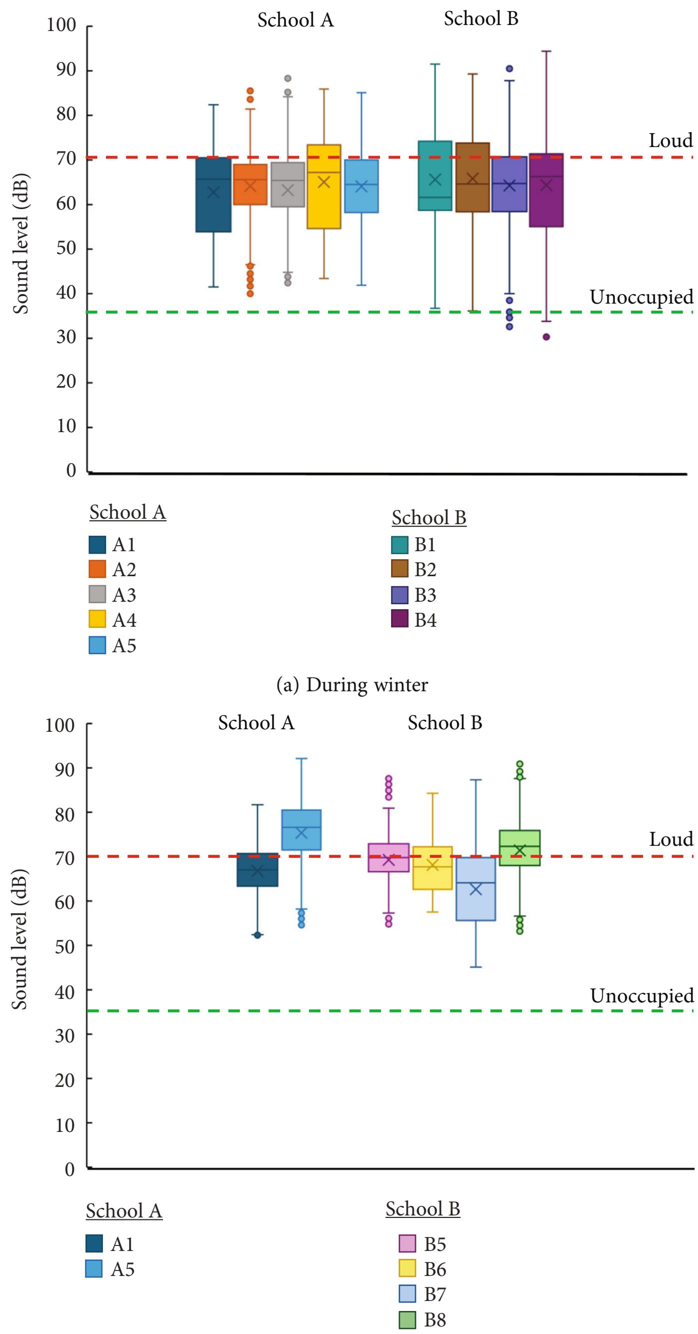
(a) During winter

(b) During summer

FIGURE 10: Boxplot of relative humidity (RH) in two schools.

3.2. Air Temperature and RH. Air temperature measurements across the two schools reflected seasonal variations and differences in ventilation strategies—natural ventilation in winter and mechanical systems in summer. In School A, winter indoor temperatures ranged from 22.5°C to 24.5°C, whereas summer values varied between 23°C and 27.1°C. School B recorded lower averages, with winter temperatures of 19.8°C–21.3°C and summer readings between 20.7°C and 23.4°C (Figure 9).

Winter thermal comfort was assessed using the model by Haddad et al. [41], tailored for children's comfort in the Middle East (Figure 9a), and summer conditions were assessed against Saudi Energy Efficiency Center [61] guidelines, which recommend 23°C –25°C for cooling (Figure 9b).



(a) During winter

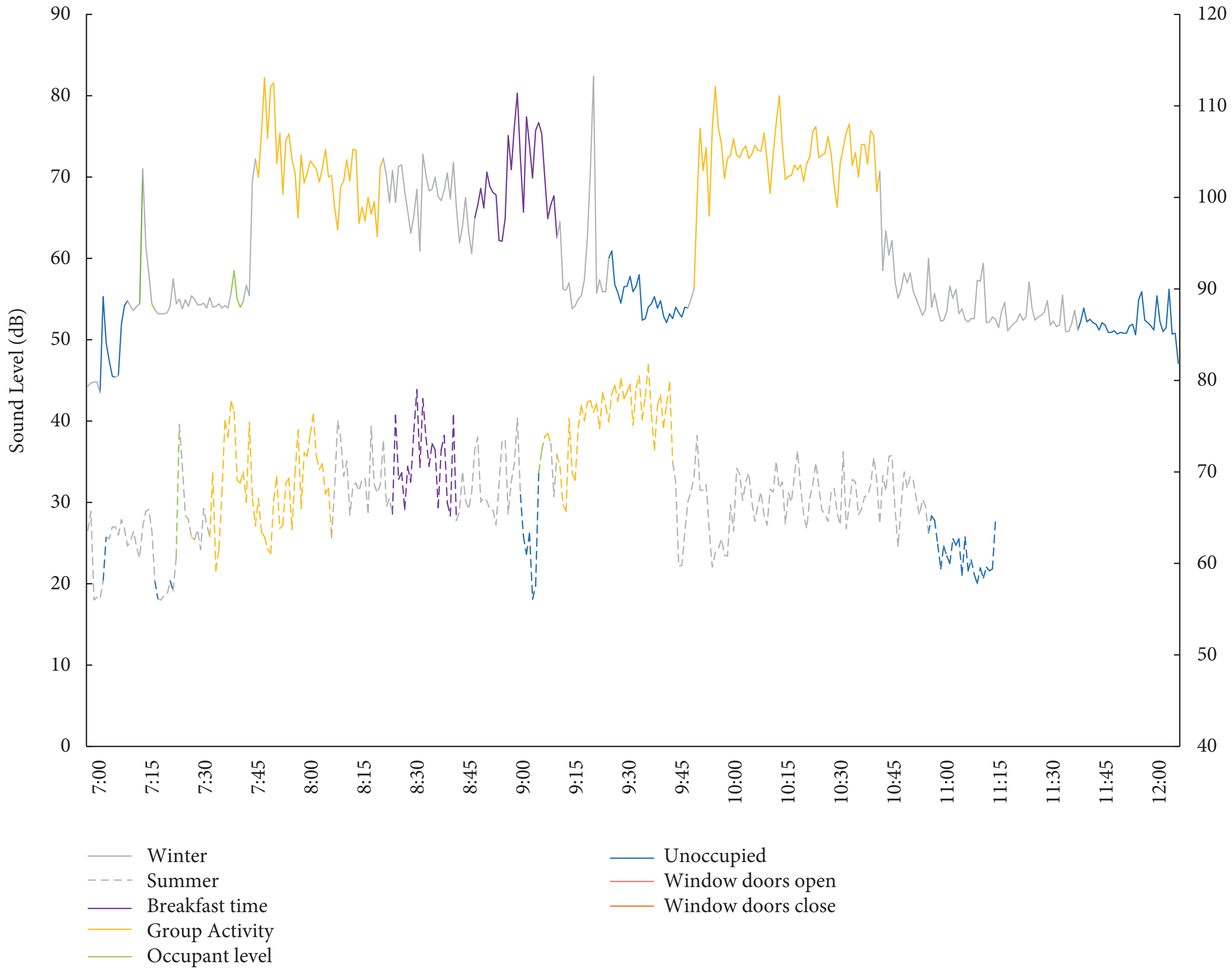
(b) During summer

Figure 11: Boxplot of sound level in two schools.

RH, as recommended by BB101 [62], should fall between 40% and 75%. School A's RH ranged from 49% to 55% in winter and 40%–46% in summer, whereas School B's RH ranged between 52% and 55% in winter and 45%–48% in summer, aligning with the recommended values (Figure 10).

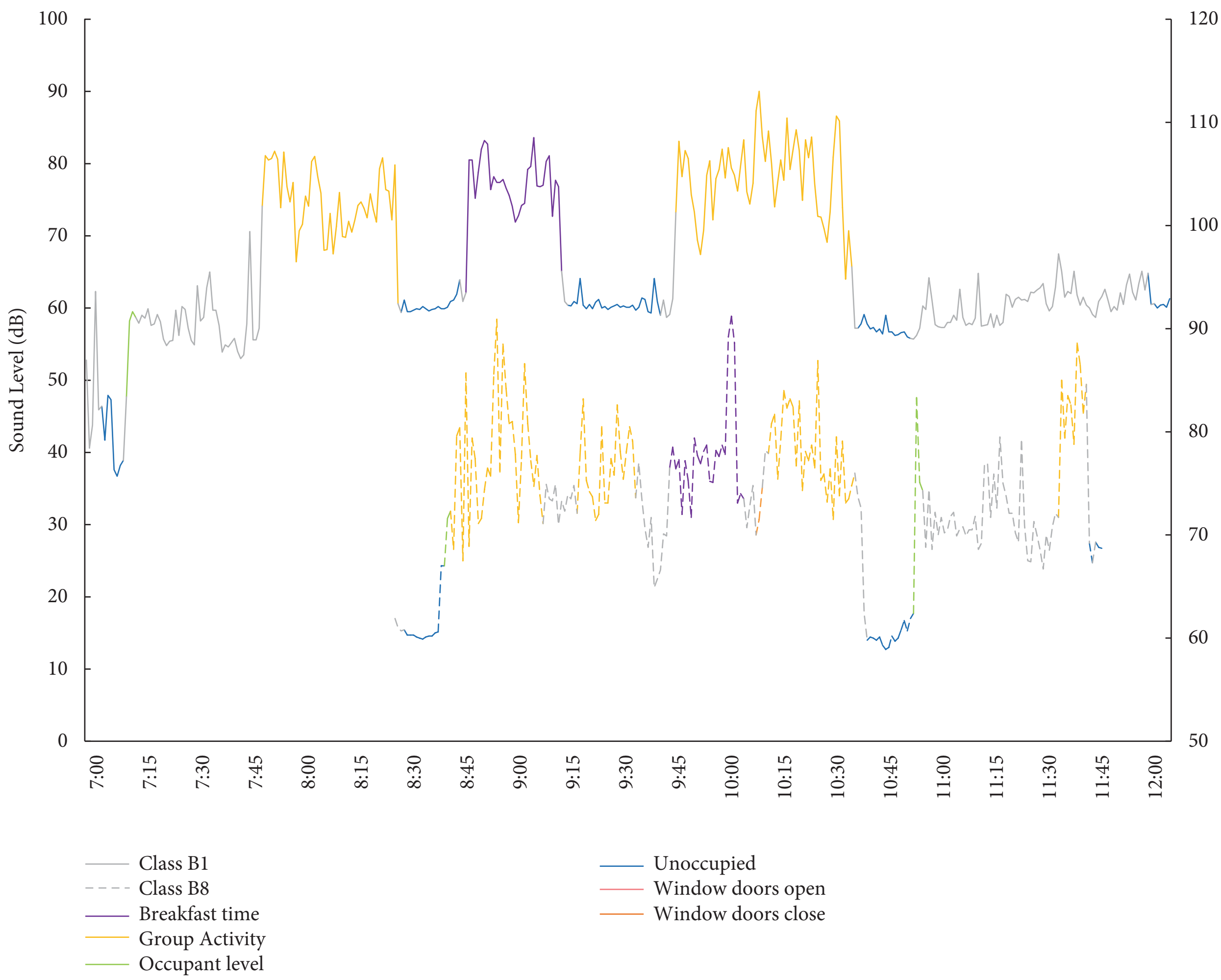
During summer, School A more frequently exceeded the recommended temperature range compared with School B. This might be due to differences in outdoor humidity during measurements, with School B experiencing higher humidity compared with School A (Figure10b). When humidity levels rise, the cooling system may struggle to remove moisture from the air, leading to increased temperatures [63, 64]. Additionally, School A's classrooms also have higher occupant density relative to room size, contributing to increased temperatures through body heat emissions [65].

Haddad et al. [41] proposed a model for children's thermal comfort in Middle Eastern schools, diverging from adult models like ANSI/ASHRAE Standard 55 [66] and Comite'Europe'en de Normalisation [67], suggesting that children prefer lower temperatures. Most



(a) Sound level profile on Classroom A1 in School A

Figure 12: Continued.



(b) Sound level profile on Classrooms B1 and B8 in School B

FIGURE 12: Profile of sound level on two schools.

winter measurements of air temperature in the observed classrooms were within the acceptable range; however, Classroom A2 in School A recorded a high temperature of 26°C. Such fluctuations may affect autistic pupils' attention and comfort, as temperature variations can influence focus. Jaber et al. [24] found that even small decreases in temperature (from 23°C to 20°C) improved attention in nonautistic pupils.

A study in a Saudi classroom found that nonautistic pupils' performance on attention tasks improved when temperatures decreased from 23°C to 20°C, highlighting a high sensitivity to even minor changes in temperature [24]. This may be relevant for autistic individuals, who often exhibit heightened sensitivity to thermal and tactile stimuli [68, 69]. Maintaining appropriate humidity levels in classrooms is equally crucial for ensuring comfort, health and sustained engagement. Elevated humidity can exacerbate discomfort, resulting in reduced concentration and increased irritability (Tsutsumi et al. 2007), while also intensifying susceptibility to sensory overload. As behaviours are fundamental to effective learning, environmental conditions that compromise these responses may consequently hinder both academic performance and social participation.

3.3. Acoustics. Sound level measurements across both schools revealed average levels exceeding the ANSI-recommended 35 dB for classrooms with mechanical ventilation [42]. In School A, winter levels ranged from 62 to 65 dB and rose to 66–75 dB in summer. School B recorded similar ranges: 63–65 dB in winter and 62–71 dB in summer (Figure 11).

The sound level profiles indicated contributions from both indoor and outdoor noise sources, such as traffic, corridor activities and ventilation and air-conditioning systems' operation on classroom acoustics (Figure 12). For example, winter measurements in Classroom A1 (54 dB) were higher than in Classroom B1 (40 dB), likely reflecting School A's proximity to a main road. This finding aligns with El-Sharkawy and Alsubaie [23], who reported comparable indoor sound levels of approximately 53 dB in similar educational settings.

Air-conditioning systems contributed to increased summer noise, particularly in School B, where average

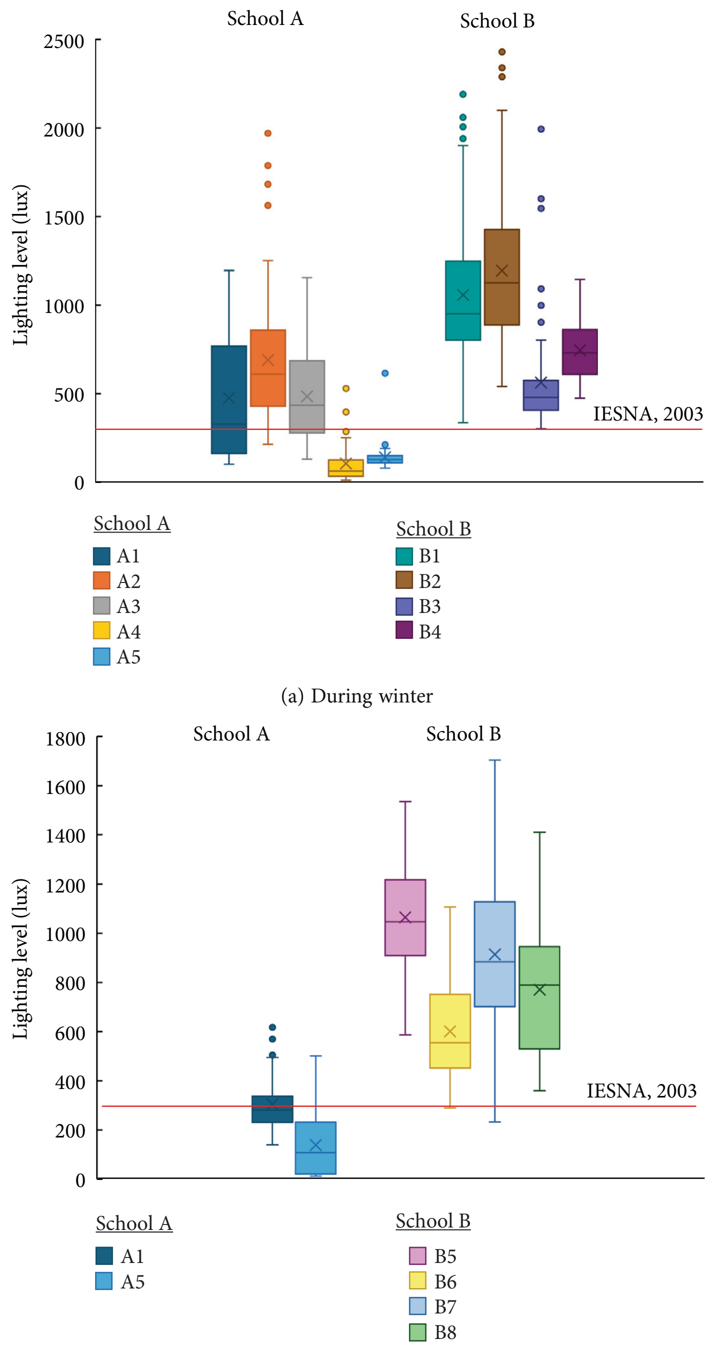
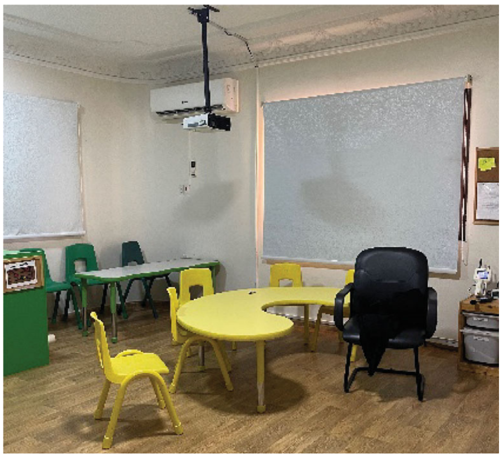


Figure 13: Boxplot of lighting level (illuminance) on two schools.

background levels reached 63 dB, compared with 47 dB in School A, which used quieter split units. High sound levels can impact auditory processing and learning, particularly in sensitive pupils [70].

Classroom activities also contribute to increased noise levels, particularly those that involve interaction, such as physical activities designed to improve communication and social skills. These activities tend to generate more noise compared with traditional lecture-based teaching commonly found in mainstream schools [71]. Additionally, noise levels can be influenced by the vocalisations associated with autistic pupils' maladaptive behaviours. A study in autistic classrooms found that sound levels exceeding 70 dB were often associated with specific behaviours, such as repetitive speech, loud vocalisations and complaints [72]. Such sensory behaviours are common in autism classrooms due to communication challenges [73].

3.4. Lighting. Lighting levels (illuminance) across classrooms in both schools showed significant variation relative to the IESNA-recommended standard of 300 lux at 0.85 m as per the Illuminating Engineering Society of North America



(a) Classroom A1 during summer shade on to avoid heat in School A

(b) Classroom A2 in School A

(c) Classroom B4 in School B

FIGURE 14: Lighting preference and shade in different classes.

(IESNA) [74, 75]. In School A, winter lighting levels ranged from 115 to 712 lux, higher than the summer range of 139–304 lux. In contrast, School B had higher lighting levels during summer, ranging from 601 to 1704 lux, compared with winter levels, which ranged from 562 to 1194 lux (Figure 13). This seasonal discrepancy is due to School A's use of shading during summer, unlike School B, which lacks window shading. Lighting variability in School A was further influenced by its adjustable lighting systems, unlike School B where large, unshaded windows limited control (Figure 14). This structural difference contributes to fluctuations in lighting conditions.

Study measured data of illuminance underscores the significant influence of autistic pupils' preferences on classroom lighting levels, alongside variations due to activities and the physical architecture of classrooms (Figure 14). Autistic pupils often adjust lighting fixtures and shading according to their immediate needs, reflecting their unique sensitivity to lighting, as shown in a survey revealing a significant difference in lighting preferences among autistic individuals [39]. Vilcekova et al. [20] also reported variability in lighting levels across special needs classrooms, ranging from 53 to 412 lux, which was attributed to weather conditions and window design. The ability to modify lighting levels is critical for autistic pupils, who may experience photosensitivity [8], highlighting the need for adaptable lighting systems tailored to their sensory needs.

Additionally, the measurement of lighting ranges in one classroom was notably wide; for example, Classroom B1 in School B had lighting levels ranging from 700 to 1500 lux, compared with mainstream classrooms where variability was more consistent, typically ranging between 400 and 800 lux [76]. This variation was linked to different classroom activities, such as using smart boards and relaxation periods, which necessitate dimmed lighting and shading.

Illuminance levels exceeding 715 lux may contribute to visual discomfort, glare and increased sensory load, particularly for autistic pupils who are more sensitive to bright and diffuse light [77]. Over-illumination can make it more difficult to maintain visual focus, increase fatigue and heighten the likelihood of sensory overstimulation, potentially affecting engagement and self-regulation in classroom activities [37]. Adjusting lighting intensity to activity type and incorporating dimmable or diffuse lighting controls may therefore be necessary to support comfortable visual conditions.

4. Conclusion

This is the first study in Saudi Arabia to investigate IEQ in autism-specific schools, establishing a baseline for current conditions and highlighting key differences from mainstream schools. The findings reveal notable seasonal and interschool variations influenced by contextual and architectural factors:

- This study provides foundational insights into the IEQ conditions of autism schools in Saudi Arabia, illustrating the influence of local climate, cultural practices and architectural features.
- Autism schools exhibit unique environmental characteristics compared with mainstream schools, shaped by sensory preferences and classroom activity schedules.
- Classrooms in both schools frequently exceeded recommended IAQ standards, mainly due to indoor sources such as incense burning and cleaning agents, particularly during winter.
- Elevated sound levels were driven by indoor activities, pupil behaviours and mechanical ventilation, differing from the traffic-related noise typical in mainstream schools.
- Significant intraclassroom lighting variation reflected the need for activity-based and sensory-sensitive lighting adjustments, unlike the uniform lighting in mainstream classrooms.

These findings highlight the need for tailored IEQ interventions in autism schools, including improved ventilation, adaptive thermal controls, indoor noise reduction strategies and flexible lighting systems. In particular, incorporating acoustic design measures—such as sound-absorbing ceiling and wall finishes, improved door and window sealing and spatial planning to distance classrooms from noise sources—can help reduce background noise and support sensory comfort. Such measures are essential for creating supportive, sensory-sensitive learning environments that promote autistic pupils' well-being and academic performance.

4.1. Limitations. This study provides initial insights into IEQ conditions in autism classrooms; however, several limitations should be noted. First, the scope was limited to two schools in the Eastern Province of Saudi Arabia, which may affect the generalisability of the findings to other regions or climates. Second, data collection was confined to selected periods in winter and summer, potentially overlooking seasonal variations throughout the year. In addition, natural variations in pupils' behaviour and activity levels may have influenced certain environmental parameters, such as noise and particulate resuspension; however, such variation is inherent in real-world autism classroom settings. Lastly, the study did not measure certain relevant parameters, such as reverberation time, glare and surface temperatures, which could provide a more comprehensive understanding of environmental impacts on autistic pupils' learning and well-being.

4.2. Recommendation for Future Research. To enhance the generalisability of findings, future research should include a wider range of autism schools across diverse regions and climates. Although no standardised IEQ benchmarks currently exist for autism-specific settings, this study offers valuable preliminary insights that can inform future standards. Given the unique sensory and behavioural needs of autistic pupils, existing guidelines may not be fully adequate. Future studies should also explore how IEQ parameters influence cognitive and behavioural outcomes in autistic pupils, helping to develop strategies that optimise their learning environments.

Targeted interventions—such as advanced ventilation systems, adaptive lighting controls and inclusive design strategies—should be implemented and evaluated to support these needs.

A tiered strategy is proposed to enhance IEQ in autism-specific classrooms as follows:

4.2.1. Short-Term/Low-Cost Measures. Immediate actions should focus on behavioural and operational practices, such as avoiding incense or other particulate-emitting products, increasing ventilation during high-activity periods and maintaining air-conditioning and filtration systems regularly.

4.2.2. Medium-Term/Design Interventions. Design improvements should include installing mechanical ventilation or air-filtration systems with HEPA filters, adopting dimmable and indirect lighting to minimise glare and integrating sound-absorbing finishes and improved door or window sealing to reduce noise transmission and support sensory comfort.

4.2.3. Long-Term/Policy Actions. Policy initiatives should be aimed at establishing autism-specific IEQ standards—such as stricter PM thresholds (e.g., $PM_{2.5} < 15\,\mu g/m^3$)—mandate post-occupancy IEQ evaluations in special education settings and embed inclusive IEQ guidelines within national building codes and educational infrastructure policies.

Policymakers and practitioners are encouraged to integrate these findings into educational infrastructure planning by updating building codes, mandating IEQ standards for special education settings and requiring post-occupancy evaluations of air quality and acoustics. A multifactorial research approach will further support the creation of inclusive, evidence-based design and regulatory frameworks.

Appendix

Time	Activity type	Occupants' number	Windows conditions	Doors conditions	Note

Figure A1: Activity observation table.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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