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Assessing and Prioritising Green Technology Interventions for Sustainable Retrofitting of Malaysian School Buildings

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ABSTRACT

School buildings in Malaysia, particularly those constructed between the 1970s and early 2000s, were developed with limited consideration for energy efficiency (EE) and climate-responsive design, resulting in high operational energy consumption and suboptimal indoor environmental conditions. In hot and humid tropical climates, cooling and lighting systems make up a substantial portion of the electricity demand in educational facilities. Although green technology retrofitting is widely recognised as an effective strategy for improving building performance, the decision to retrofit public schools remains constrained by the lack of context-specific prioritisation approaches. Therefore, this study aimed to identify and prioritise suitable green technology interventions for retrofitting Malaysian school buildings. A structured literature review was conducted to identify potential retrofit measures, which were subsequently categorised into three domains, namely, energy efficiency (EE), indoor environmental quality (IE), and smart operational controls (SO). A questionnaire survey involving 52 certified energy auditors in Malaysia was then conducted to evaluate the relative importance of each intervention. The findings identified heating, ventilation, and air conditioning (HVAC) system improvements, energy-efficient lighting upgrades, reflective roof treatments, window sealing enhancements, shading applications, and energy monitoring practices as being among the most significant retrofit strategies for Malaysian school buildings. The study contributes by providing a climate-responsive prioritisation basis, integrating technical feasibility, economic considerations, and operational practicality. The findings from this research may serve as a useful foundation for the future development of retrofit decision-making frameworks and strategic planning approaches for public school buildings in resource-constrained environments.

Keywords: Green retrofit prioritisation; school building retrofitting; tropical climate buildings; Relative Importance Index (RII); energy efficiency strategies

INTRODUCTION

Growing worldwide energy consumption, coupled with accelerating environmental degradation and climate change, underscores the urgent need for sustainable practices across all sectors, especially within the built environment. Schools, which are a vital part of public infrastructure, consume a significant amount of energy because they depend heavily on artificial lighting and mechanical cooling systems (Zamani & Amiri 2024). In tropical countries like Malaysia, where average daily temperatures often exceed 30°C and the relative humidity frequently surpasses 80%, cooling and lighting alone can account for 50–70% of a school's total electricity usage (Chemingui et al. 2020).

Despite the growing awareness of sustainability, more than 60% of Malaysian schools are outdated, having been built between the 1970s and early 2000s, when energy efficiency (EE) considerations were minimal (Ali et al. 2024). These facilities typically lack adequate insulation, shading, and passive ventilation, resulting in higher operational costs and poorer indoor environmental quality (IE) that negatively impact the comfort and learning performance of students. Studies indicate that schools without retrofits consume up to 40% more energy than those that have been upgraded with energy-efficient measures (Heracleous et al. 2021).

Aldawoud et al. (2020) argued that although some retrofitting efforts have been made, these are often unsystematic and inconsistent, mainly due to the absence of a clear, climate-appropriate evaluation framework for existing educational facilities. This deficiency compels school administrators, many of whom lack technical expertise in energy management or sustainable building design, to make retrofit decisions without adequate guidance (Cecconi et al. 2019). Current green building rating tools, while generally applicable, do not offer the specificity required for the tropical, budget-constrained environment of Malaysian public schools.

This research sought to pinpoint, categorise, and rank green technology interventions for retrofitting Malaysian school buildings. Measures were outlined across three main areas, namely, EE, IE, and smart operational controls (SO), based on an extensive review of both international and local academic literature. A targeted survey of 52 energy auditors in Malaysia, chosen for their expertise in sustainable design and building performance, was conducted to evaluate the significance of each measure. The relative importance index (RII) method was then used to quantitatively rank these measures based on their climatic applicability, cost-effectiveness, and performance impact, thereby establishing a context-specific prioritisation approach for Malaysian school retrofit applications (Tan et al. 2023). This framework aimed to ensure that retrofit initiatives are optimally aligned with national sustainability objectives and resource constraints (Ahmed et al. 2024).

This research provides a decision-making tool for stakeholders to optimise retrofit investments, combining expert opinions with a systematic analytical method. The resulting prioritisation approach helps to allocate resources more efficiently so as to maximise environmental and operational benefits and also aligns with the national sustainability targets and energy conservation objectives of the Ministry of Education. This approach ensures that retrofit initiatives are tailored to the challenges of Malaysian schools while promoting long-term sustainability and an improved learning environment (Mohamad et al. 2020).

PROBLEM STATEMENT

School buildings in Malaysia, particularly those constructed between the 1970s and early 2000s, were designed without regard for modern energy-efficiency standards. In tropical climates, these facilities consume disproportionately high amounts of energy, with cooling and lighting alone accounting for 50–70% of total electricity use (Chung-Camargo et al. 2022). Most government-funded schools lack adequate insulation, shading, or passive ventilation, resulting in elevated operational costs and suboptimal IE (Mohelníková et al. 2020). These inefficiencies not only strain the energy budget of the Ministry of Education but also adversely affect student comfort and learning outcomes.

Although numerous green building rating tools provide general guidelines for EE assessments, their criteria are often too broad and insufficiently adapted to the specific climate, infrastructure age, and budgetary realities of Malaysian public schools (Kamil et al. 2018). Retrofitting decisions in these institutions are, therefore, frequently ad hoc, inconsistent, and heavily influenced by individual judgment rather than a structured evaluation. The absence of a structured prioritisation approach means that school administrators, many of whom lack technical expertise, struggle to select the most suitable interventions to balance performance, affordability, and implementation feasibility (AlFaris et al. 2016). Furthermore, existing studies on school retrofits often focus narrowly on EE or environmental impacts, overlooking comprehensive occupant-centric metrics such as cognitive performance (Dong et al. 2023).

Previous studies and initiatives, including the Malaysian Eco Schools Programme, advocated for energy conservation. However, they infrequently addressed the prioritisation of the interventions required for optimising resource allocations. Reported energy savings from retrofit projects exhibit significant variations, typically between 10–35%, primarily due to the inconsistent selection of measures and insufficient contextual adaptations (Ben & Steemers 2020). This variability leads to missed opportunities for maximising performance and achieving national sustainability targets. Thus, the lack of a comprehensive framework for assessing and prioritising green technology interventions in Malaysian public schools represents a critical gap, hindering effective decision-making and the realisation of broader sustainability objectives (Ali & Sameh 2024).

Therefore, a practical, evidence-based prioritisation framework is needed to guide decision-makers in identifying potential retrofit measures that would have the most significant impact (Seeley & Dhakal, 2021). Accordingly, this study sought to answer the question as to which green technology retrofit interventions should be prioritised to improve the sustainability performance of Malaysian public school buildings within the context of the country's tropical climate. The RII method was applied to rank non-energy-generation green technology interventions such as ductwork sealing, light-emitting diode (LED) lighting retrofits, reflective roof coatings, and passive ventilation measures based on expert evaluations of climatic suitability, cost feasibility, and performance potential. This approach aimed to overcome the limitations of current generalised green building assessment tools by providing a context-specific, data-driven methodology for enhancing the sustainability and operational efficiency of Malaysian school buildings (Shari et al. 2023).

LITERATURE REVIEW

CONCEPT OF GREEN TECHNOLOGY IN BUILDING RETROFITTING

Green technology in the built environment refers to the integration of materials, systems, and processes designed to reduce environmental impacts, improve resource efficiency, and enhance occupant well-being (Tan et al. 2021). Within the context of the retrofitting and upgrading of existing building infrastructure to meet contemporary performance and sustainability standards, the application of green technologies is gaining recognition as a cost-efficient alternative to new constructions, particularly in public sector settings with limited budgets (Jin & Marjanovic-Halburd 2018). Retrofitting not only mitigates energy and water consumption but also preserves the embodied energy of existing structures, thereby contributing to a lower overall environmental footprint (Oh et al. 2025).

Studies have consistently demonstrated that integrating green technologies into retrofit projects yields significant measurable benefits. For instance, Madushika et al. (2023) reported reductions of 20-50% in operational energy use in educational facilities following the installation of high-efficiency heating, ventilation, and air conditioning (HVAC) systems, LED lighting, and photovoltaic arrays. In tropical conditions, reflective roofing systems, cool roof coatings, and vegetative shading have been shown to reduce cooling energy demand by 8–15%, thereby alleviating the reliance on mechanical cooling systems (Ullah et al. 2021). Water conservation technologies such as rainwater harvesting, greywater reuse, and low-flow plumbing fixtures have been successfully deployed in schools to reduce the demand for potable water, with documented savings of up to 30% annually in areas facing water stress (Moghayedi et al. 2023).

The benefits of integrating green retrofit technologies, such as enhanced IE through improved ventilation, air filtration, daylight access, and acoustic performance, extend beyond environmental performance (Elkhapery et al. 2022). These improvements have been linked to better student concentration, reduced absenteeism, and higher academic achievement (Sanz-Mas et al. 2024). Despite this evidence, the adoption of such interventions in Malaysian schools remains low. Common obstacles include significant upfront capital costs, a scarcity of technical expertise in green building practices, inadequate governmental incentive programmes, and the absence of clear, context-specific guidance for administrators (Darko & Chan, 2016). These challenges highlight an urgent need for research to identify, contextualise, and prioritise suitable green technologies for school retrofits in Malaysia's tropical climate (Tetteh et al. 2022). In this case, it is necessary to prioritise retrofitting based on levels of priority, especially in developing countries with limited resources.

GLOBAL AND LOCAL PERSPECTIVES ON GREEN TECHNOLOGY FACTORS

Tetteh et al.'s (2022) elaboration on international sustainability frameworks provides a helpful reference point for identifying relevant green technology factors in retrofit contexts. The Leadership in Energy and Environmental Design rating system, developed by the U.S. Green Building Council, assigns points across categories, including sustainable sites, water efficiency, energy and atmosphere, materials and resources, and IE (Asdrubali et al. 2021). Similarly, the Building Research Establishment Environmental Assessment Method, originating in the United Kingdom, emphasises life-cycle environmental performance and operational management alongside core design interventions (Building Research Establishment (BRE), 2016; Ding, 2008). Australia's Green Star framework adapts these principles to diverse climate zones and offers tailored modules for educational facilities, incorporating comfort metrics such as daylight levels and ventilation rates (Heracleous et al. 2021).

Malaysia's Green Building Index, introduced in 2009 in response to both global best practices and local climatic realities, is the national benchmark for sustainable buildings (Norazman et al. 2021). The Green Building Index score gives the most significant weight to EE (~35%), followed by IE (~21%), with the remaining categories covering sustainable site planning, materials and resources, water efficiency, and innovation credits. Hazem et al. (2020) noted that the Green Building Index explicitly incorporates passive cooling, optimal building orientation, shading systems, and humidity control measures to mitigate the characteristically hot and humid tropical climate of Malaysia (Tan et al. 2023).

Comparative studies suggest that while these frameworks agree on the core categories, their applicability varies across regional contexts. Heating efficiency measures that are prominent in temperate climates are largely irrelevant in Malaysia, where factors such as passive ventilation, rainwater management, and glare control are of greater importance (Tataresthagi et al. 2018). This divergence underscores the need to recontextualise universal green technology categories in line with local priorities.

GREEN TECHNOLOGY INTEGRATION IN EDUCATIONAL BUILDINGS

Educational buildings exhibit operational and spatial characteristics that influence the design of retrofit strategies. Moghayedi et al. (2023) highlighted that their daily schedules are predominantly concentrated during daylight hours, enabling the cost-effective use of passive daylighting and, in some cases, solar energy harvesting. In tropical climates, the priority is to mitigate solar heat gain through shading devices, ventilated façades, and cross-ventilation designs (Moreno & Ramos, 2018).

Real-world examples have demonstrated the feasibility and impact of targeted green technologies in schools. In Singapore, Salameh and Touqan (2024) observed that there was a reduction of 35% in electricity costs following LED lighting upgrades and the installation of rooftop solar photovoltaic arrays. In Japan, green roofs and vegetative shading lowered classroom temperatures by approximately 2°C, while simultaneously serving as educational resources for biology and environmental science classes (Abe et al. 2020). Pilot projects in Malaysia have shown that rainwater harvesting systems for toilet flushing and landscape irrigation can effectively reduce the reliance on municipal water during peak demand (Halim et al. 2019).

In addition to technical performance, educational retrofits yield a dual benefit when linked with education sustainability. Altobelli et al. (2020) found that student participation in retrofit-related activities, such as energy audits and the monitoring of embedded conservation behaviours, persisted beyond the formal intervention phase. This symbiotic relationship between infrastructure and pedagogy makes green retrofit technologies particularly well-suited to school contexts (Mora et al. 2018).

MAJOR GREEN TECHNOLOGY FACTORS RELEVANT TO MALAYSIAN SCHOOLS

Green technology interventions for retrofitting school buildings in Malaysia can be organised into three primary performance domains, namely, EE, IE, and SO. As stated by Shahli & Akasah (2019), this streamlined categorisation approach reflects both international and local evidence, drawing on established green building rating systems, regional case studies, and local pilot implementations. It integrates relevant measures from the original five-category approach, notably water efficiency and sustainable materials, into EE and IE domains, where they logically fit (Firoozi et al. 2025).

Energy efficiency (EE) consistently emerges as the dominant priority in global and local literature because cooling and lighting account for the largest share of electricity consumption in Malaysian schools, often exceeding 70% of total use (Samad et al. 2017). High-efficiency HVAC systems, incorporating features such as airside economisers, cooling capacity modulation, and humidity regulation, can markedly reduce energy use while preserving thermal comfort (Zhu & Li 2025). Fan system upgrades, including the adoption of ENERGY STAR-certified models, electronically-commutated motor retrofits, and sensor-based controls, further improve air movement efficiency in classrooms and halls (Kaczmarek 2025). Lighting retrofits, particularly the replacement of fluorescent lamps with LED systems paired with occupancy sensors and zoning controls, consistently deliver energy reductions of between 40–60% without diminishing illumination quality (Aghajari & Chen, 2025). Measures that improve water efficiency, such as variable pressure pumps or low-flow fixtures, are also relevant in the EE domain because they reduce the use of operational energy in pumping and heating systems (Cagno et al. 2022).

Improvements in IE address thermal comfort, ventilation, daylighting, and acoustic performance, all of which directly influence learning environments and indirectly contribute to energy savings (Martínez et al. 2021). Passive strategies such as cross-ventilation window placements, ventilated façades, and shading devices can substantially lower indoor cooling loads while maintaining occupant comfort. Optimised daylighting, achieved through window-to-wall ratio adjustments, light shelves, and solar control glass, not only reduces the reliance on artificial lighting but also supports cognitive performance and visual comfort (Kunwar et al. 2020). Acoustic enhancements, such as sound-absorbing panels, mitigate the background noise that disrupts learning (Kaczmarek, 2025). Sustainable material choices are embedded within the IE domain in this framework, recognising that low-volatile organic compound paints, adhesives, and sealants improve indoor air quality. In contrast, recycled and locally sourced materials reduce the embodied carbon and are aligned with local construction traditions (Affolderbach & O'Neill 2023).

Smart operational controls (SO) enable schools to sustain a high performance over time by continuously monitoring and optimising energy and environmental systems. Building management systems or modular intelligent controls can automate HVAC, lighting, and water operations based on occupancy patterns and environmental data, thereby ensuring the efficient use of resources (Azzi et al. 2024). Sub-metering for energy and water allows administrators to pinpoint high-consumption zones and tailor conservation efforts (Iwayemi et al. 2011). Advanced monitoring tools, such as carbon footprint dashboards, provide actionable data for long-term emissions-reduction planning aligned with Malaysia's sustainability ambitions. Majekodunmi et al. (2023) added that these operational strategies serve as critical enablers for EE and IE improvements, ensuring that physical retrofits translate into long-term performance gains.

These integrated domains collectively establish a structured basis for evaluating retrofit measures and identifying and prioritising retrofit interventions in Malaysian schools. This approach effectively balances environmental performance, occupant well-being, and economic viability (Mohd-Rahim et al. 2017). By integrating the physical infrastructure with operational management, this holistic strategy supports policymakers, school administrators, and design professionals in developing retrofit plans that are technically sound, climate-appropriate, and resource-efficient (Dong et al. 2023). Given the exploratory and inclusive nature of the framework in its development stage, both low-cost and advanced retrofit technologies reported in the literature were considered at this point, with contextual suitability and feasibility evaluated later through expert-based prioritisation. The complete set of green technology retrofit measures identified from the literature and organised under the three performance domains is summarised in Table 1.

TABLE 1. The EE retrofit measures for school buildings

Code	Sub-Criteria & Factor	Key Benefit	Key Literature
		ENERGY EFFICIENCY (EE)	
		HVAC Systems (EE-HVAC)	
EE-HVAC-01	Installation of airside economiser.	Utilises fresh air to reduce cooling load.	Moazzen et al. (2020)
EE-HVAC-02	Sealing and maintenance of ductwork.	Prevents leakage and improves efficiency.	Elkhapery et al. (2022)
EE-HVAC-03	Installation of fan speed controls.	Optimises airflow to match demand.	Khazaee et al. (2024)
EE-HVAC-04	Installation of cooling capacity controls.	Matches output to load.	Liu et al. (2025)
EE-HVAC-05	Installation of cooling temperature and humidity controls.	Enhances comfort and reduces waste.	Mora et al. (2018)
EE-HVAC-06	Scheduling of regular HVAC maintenance for improved efficiency.	Sustains performance.	Dong et al. (2023)
		Fan Systems (EE-FAN)	
EE-FAN-01	Installation of ENERGY STAR-certified fan systems.	Provides higher airflow for less energy.	Kyritsi et al. (2023)
EE-FAN-02	Installation of motion sensor for automatic power on and off switches.	Prevents energy wastage.	Khazaei et al. (2025)
EE-FAN-03	Installation of fan speed sensor controls.	Auto-adjusts fan speed.	Peiris et al. (2025)
EE-FAN-04	Replacement of AC motors with electronically-commutated fans for improved efficiency.	Improves efficiency.	Willis et al. (2024)

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Internal Lighting & Illumination (EE-LIT)			
EE-LIT-01	Installation of occupancy-based light sensors.	Auto turns off of lights when unused.	Shrestha & Rijal, (2023)
EE-LIT-02	Design and commensurate set up of illuminance intensity.	Matches lighting needs.	Gigante et al. (2024)
EE-LIT-03	Assessment of lighting quantity.	Avoids over-lighting.	Sorace et al. (2024)
EE-LIT-04	Installation of energy-saving LED bulbs.	Significantly reduces energy use.	Elkhapery et al. (2022)
EE-LIT-05	Set up of lighting zones and controls.	Allows selective lighting.	Karakas et al. (2023)
EE-LIT-06	Implementation of lamp colour temperature.	Improves comfort.	Alamin et al. (2023)
External Lighting & Illumination (EE-LEX)			
EE-LEX-01	Installation of light dimmers.	Adjusts output to ambient needs.	Heracleous et al. (2023)
EE-LEX-02	Installation and utilisation of lighting timers.	Reduces unnecessary operation.	Aloshan & Aldali, (2024)
EE-LEX-03	Determination of lighting placement for optimal luminance.	Improves lighting coverage with fewer fixtures.	Akkose et al. (2021)
EE-LEX-04	Replacement of standard bulbs with energy-saving LED bulbs.	Reduces energy use outdoors.	Kaczmarek, (2025)

The EE measures presented in Table 1 mainly targeted the reduction of operational energy consumption associated with cooling, ventilation, and lighting systems within school buildings. In tropical educational environments such as in Malaysia, these systems contribute significantly to the overall electricity demand, making EE interventions particularly important for improving building sustainability and reducing long-term operational costs. The identified measures also reflected retrofit strategies that are generally practical, scalable, and suitable for implementation within the existing public-school infrastructure.

TABLE 2. The IE retrofit measures for school buildings

INDOOR ENVIRONMENTAL QUALITY (IE)			
Window (IE-WIN)			
IE-WIN-01	Installation or replacement of low-emissivity glazing.	Reduces heat gain and improves insulation.	Mora et al. (2018)
IE-WIN-02	Application of solar film to reduce external heat gain.	Reduces cooling load.	Kamalakannan et al. (2021)
IE-WIN-03	Increasing of window-to-wall ratio for natural ventilation and lighting.	Improves daylight and natural ventilation.	Zacki & Pathirana, (2025)
IE-WIN-04	Installation of venetian blinds.	Controls glare.	Grassie et al. (2022)
IE-WIN-05	Improvement of the window seal to increase airtightness.	Prevents infiltration.	Song et al. (2024)
IE-WIN-06	Filling of gas between glass layers to serve as insulation.	Provides better insulation.	Khazaee et al. (2024)
IE-WIN-07	Mounting of additional overhangs for windows.	Limits solar gain.	Yu et al. (2025)
Roof (IE-ROF)			
IE-ROF-01	Installation, addition, or renovation of roof insulation.	Reduces heat transfer.	Alsukkar et al. (2025)
IE-ROF-02	Installation, addition, or renovation of roof coating.	Reduces solar absorption.	Ouali et al. (2025)

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IE-ROF-03	Replacement of roof material replacement, such as the metal, slate, and clay to name a few.	Improves durability and thermal performance.	Tang et al. (2024)
IE-ROF-04	Use of reflective, light coloured paint for heat reduction.	Prevents heat build-up.	Vassiliades, (2024)
IE-ROF-05	Installation of roof overhangs/ awnings for shading in hot climates.	Provides shade.	Xiao et al. (2023)
	Ceiling (IE-CEI)		
IE-CEI-01	Installation, addition, or renovation of ceiling insulation.	Prevents heat transfer from roof.	Rahemipoor et al. (2023)
IE-CEI-02	Upgrade to certified ENERGY STAR-certified ceiling fan.	Provides efficient cooling.	Poudhar & Ghosh, (2025)
IE-CEI-03	Replacement of ceiling with phase change material panels.	Stabilises room temperature.	Qiu et al. (2025)
IE-CEI-04	Use of light, reflective ceiling paint in hot climates.	Improves light efficiency indoors.	Vassiliades, (2024)
IE-CEI-05	Installation of specialised ceiling panels for radiant cooling.	Provides targeted cooling.	Sheng et al. (2025)
	Wall (IE-WAL)		
IE-WAL-01	Renovation of external wall insulation and fixing of seal joints.	Improves thermal performance.	Wang et al. (2024)
IE-WAL-02	Installation, addition, or renovation of internal wall insulation.	Enhances comfort.	Calama-González et al. (2025)
IE-WAL-03	Mounting of shading elements to protect from direct sunlight.	Prevents direct sun exposure.	Wen et al. (2023)
IE-WAL-04	Installation of radiant wall cooling.	Maintains cool surfaces.	Zinzi et al. (2021)
	Floor (IE-FLR)		
IE-FLR-01	Upgrade of insulation to improve airtightness.	Minimises air leakage.	Valentini et al. (2025)
IE-FLR-02	Replacement of floor finishes for better thermal efficiency.	Improves comfort.	Pandey et al. (2025)
IE-FLR-03	Installation of radiant floors or slab cooling systems.	Provides even temperature distribution.	Yue et al. (2024)
IE-FLR-04	Application of reflective floor coating to enhance lighting.	Improves brightness.	Leif & Loftness, (2024)
	Façade (IE-FAC)		
IE-FAC-01	Upgrade of façade insulation to reduce thermal bridging.	Reduces thermal bridging.	Han et al. (2023)
IE-FAC-02	Use of high-performance façade elements for thermal benefits.	Improves thermal performance.	Moreno & Ramos (2018)
IE-FAC-03	Selection and installation of proper types of façade materials.	Ensures local suitability.	Skalar et al. (2025)
IE-FAC-04	Upgrade of façade's glazing system to improve ventilation.	Improves daylight and ventilation.	Feng et al. (2022)
IE-FAC-05	Installation of double-skin façade.	Provide passive cooling layer.	Cholewa et al. (2023)

The IE measures summarised in Table 2 focused on improving thermal comfort, ventilation performance, daylight utilisation, and overall occupant well-being within school environments. These interventions are particularly relevant in hot and humid climates, where excessive heat gain and inadequate ventilation can negatively affect indoor comfort and learning conditions. Many of the identified measures also contribute indirectly to energy reduction by minimising the dependence on mechanical cooling systems.

TABLE 3. The SO retrofit measures for school buildings

SMART OPERATIONAL CONTROLS (SO)			
Energy Management (SO-ENG)			
SO-ENG-01	Critical analysis of carbon footprint mitigation strategies.	Guides reductions in emissions.	Ouali et al. (2025)
SO-ENG-02	Installation of sub-meter to monitor and measure energy use.	Monitors consumption.	Grassie et al. (2022)
SO-ENG-03	Management and monitoring of electrical appliance inventory.	Avoids unnecessary use.	Feng et al. (2022)
SO-ENG-04	Installation of electricity-based backup generator.	Improves resilience.	Pandey et al. (2025)
SO-ENG-05	Application of intelligent control systems.	Automates optimisation.	Heracleous et al. (2021)
Water Monitoring (SO-WAT)			
SO-WAT-01	Installation of sub-meters to monitor facility’s energy use.	Tracks energy use patterns.	Khazaee et al. (2024)
SO-WAT-02	Installation of energy-saving water pumps with variable pressure control.	Reduces pump energy use.	Bikas et al. (2017)
SO-WAT-03	Installation of ENERGY STAR-certified water heaters.	Provides efficient water heating.	Elkhapery et al. (2020)

The SO measures listed in Table 3 emphasised the role of monitoring, automation, and operational optimisation in maintaining sustainable building performance. These interventions support the long-term effectiveness of retrofit strategies by enabling the continuous monitoring of energy and resource consumption, improving operational efficiency and assisting school administrators in making data-driven facility management decisions.

Although previous studies discussed green retrofitting and sustainable school buildings, very few studies prioritised green technology retrofit interventions, specifically for Malaysian public-school buildings within the context of a tropical climate. This gap has limited the availability of a structured guide for selecting suitable retrofit measures in Malaysian schools. Therefore, this study aimed to identify and prioritise suitable green technology retrofit interventions for Malaysian school buildings using the RII analysis.

RESEARCH METHODOLOGY

RESEARCH DESIGN

This investigation employed a descriptive-analytical research methodology, integrating a structured literature review with expert-driven quantitative prioritisation (Khazaei et al. 2025). The core aim was to identify, classify, and rank green technology retrofit strategies for Malaysian school buildings structured across three theoretically supported domains, namely, EE, IE, and SO. These domains were consistent with established principles from international building performance frameworks, such as the Leadership in Energy and Environmental Design rating system, the Building Research Establishment Environmental Assessment Method (BREEAM), and Malaysia’s Green Building Index, as well as empirical findings from studies on tropical building retrofits (Tuck et al. 2020). Collectively, these domains encompassed enhancements to physical systems, improvements in environmental performance, and strategic operational approaches, all contributing to the creation of sustainable, high-performing educational environments within Malaysia's hot and humid climate (Johari & Said, 2021).

Figure 1 presents the structured workflow of the data analysis process adopted in this study. The framework integrated the synthesis of systematic evidence, an expert-driven evaluation, and quantitative prioritisation techniques to ensure a robust and context-specific assessment of green retrofit interventions for Malaysian school buildings.

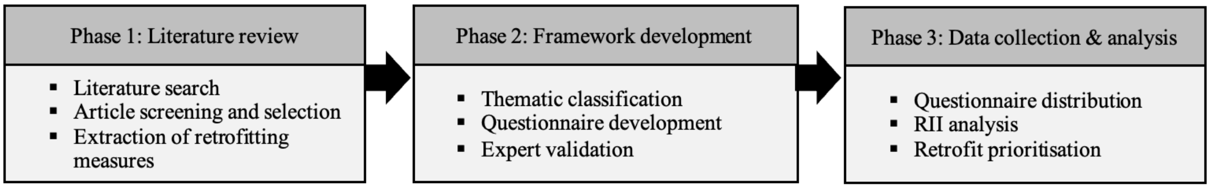

FIGURE 1. A flowchart of the data analysis process

LITERATURE SEARCH AND SCREENING

A structured literature review approach was adopted to improve the transparency and consistency of the article selection process. The research began with an extensive review of academic and professional publications to identify green technology retrofit options suitable for Malaysian school buildings. Peer-reviewed studies were sourced from Scopus, Web of Science, and Google Scholar using keywords such as "green retrofit", "school buildings", "energy efficiency", "sustainable retrofitting", and "tropical buildings".

To be included, documents had to be published between 2010 and 2025, concentrate on retrofits of educational or public buildings, and offer empirical or technical data relevant to hot and humid tropical climates (Tuck et al. 2020). Irrelevant records were removed after the screening of titles, abstracts, and full texts. This initial screening identified 127 articles, which were then narrowed down to 51 highly impactful ones. These 51 articles then underwent a thematic synthesis to categorise key themes and approaches in green building and retrofitting (Mohd-Rahim et al. 2017).

EXTRACTION AND CONSOLIDATION OF MEASURES

Eligible sources were systematically examined to extract discrete green technology measures. A measure was defined as a specific intervention capable of improving EE, water efficiency, IE, sustainable material use, or SO, such as installing an airside economiser (Moghayedi et al. 2023), applying solar films (Mafimisebi et al. 2018), and installing LED bulbs (Karimi et al. 2023). For each measure, the literature source, brief technical description, and reported benefits were recorded. Measures described in multiple sources were merged under a uniform terminology, ensuring all relevant citations were maintained for traceability. All the measures reported in the literature were initially retained to avoid pre-emptive researcher bias; feasibility filtering was intentionally deferred to the expert-based RII prioritisation stage.

CODING AND THEMATIC CATEGORISATION

A three-part alphanumeric code was assigned to each measure to facilitate a systematic organisation (Er-retby et al. 2025). The first part denoted the three main performance domains, namely, EE, IE, and SO. Measures related to water efficiency and sustainable materials were analytically embedded within the EE and IE domains based on their primary performance contribution, in line with the three-domain framework adopted in this study.

For example, energy-saving water pumps with variable pressure control were categorised under the EE domain due to their contribution to the reduction of operational energy consumption, while low-volatile organic compound materials and improved ventilation-related measures were integrated within the IE domain because of their direct influence on indoor comfort and occupant well-being.

The second component identified the building system or element, such as HVAC, FAN, LIT, WIN, ROF, CEI, WAL, FLR, FAC, ENG, or WAT. The final part referred to its sequential number within that system. For example, "EE-LIT-04" designates the fourth lighting-related EE measure as "installation of LED bulbs" (Ahmed et al. 2024).

RESPONDENTS SELECTION

Energy auditors registered with the Energy Commission were selected as the respondent group for the survey (Wang et al. 2024). This choice was based on their multidisciplinary expertise in EE, water sustainability, and IE interventions, as well as the availability of a public registry that enabled verifiable, location-specific sampling (Tan et al. 2021). Energy auditors are trained to evaluate retrofits holistically, integrating architectural, mechanical, electrical and environmental considerations, which align closely with the multi-criteria focus of this research.

QUESTIONNAIRE DEVELOPMENT

The questionnaire instrument was developed based on the retrofit measures identified from the literature review. Before distribution, the questionnaire was reviewed by experts, comprising an academic expert in sustainable construction and two certified energy auditors, to ensure the clarity, relevance, and suitability of the measurement items within the context of Malaysian school retrofits. Minor improvements were subsequently made to refine the wording and improve the consistency of the questionnaire before its full-scale distribution.

RELIABILITY ANALYSIS

A reliability analysis was conducted using Cronbach's Alpha to evaluate the internal consistency of the questionnaire items across the three main domains, namely, EE, IE, and SO. Cronbach's Alpha is widely applied in construction management and survey-based research to determine the reliability of measurement instruments and assess the consistency of respondent evaluations within each domain.

The reliability analysis indicated satisfactory levels of internal consistency across all three domains. According to commonly accepted reliability interpretations, Cronbach's Alpha values above 0.70 indicate acceptable reliability for exploratory and expert-based assessment studies. The EE domain recorded the highest reliability ($\alpha = 0.872$), followed by SO ($\alpha = 0.869$), while IE also demonstrated acceptable reliability ($\alpha = 0.744$). Therefore, the questionnaire instrument was considered reliable and suitable for the subsequent RII analysis.

RELATIVE IMPORTANCE INDEX (RII)

The RII method was employed to quantitatively rank the identified measures (Ruggeri et al. 2020). A structured questionnaire, listing all the coded measures from Table 1, was distributed to 52 purposively selected energy auditors. The respondents rated each measure on a five-point Likert scale (1 = very low importance, 5 = very high importance), considering climatic suitability, cost feasibility, and the expected impact on performance in the school environment. The RII results represented a prioritisation based on expert professional judgement rather than empirically measured energy or environmental performance.

SAMPLE SIZE

The adequacy of the sample size was carefully considered, given the expert-driven nature of this study and the use of the RII for the prioritisation analysis. The target population consisted of 83 registered energy auditors in Malaysia, representing the full national pool of certified professionals qualified to evaluate building energy performance and retrofit measures. From this population, 52 valid responses were obtained, resulting in a response rate of 62.7%. This level of participation is considered robust for surveys involving specialised professional groups and reflects a substantial proportion of the national expert population, thereby minimising potential sampling bias.

The sample size was methodologically justified for several reasons. Firstly, RII-based studies prioritise expert judgement over statistical generalisation, with reliability being dependent on the respondents' expertise rather than large sample sizes. Previous studies in the fields of energy retrofitting and sustainable construction have shown that 20–50 expert respondents are sufficient to produce stable and meaningful rankings. Secondly, all the respondents were certified energy auditors with direct experience in assessing retrofit interventions in Malaysia's hot and humid climate, ensuring the high informational value of each response.

The respondents involved in this study comprised registered energy auditors with professional experience in building energy assessments and retrofit practices across Malaysia. The diversity of the respondents was considered important to obtain a broader perspective regarding retrofit priorities under varying operational and environmental conditions. However, this study acknowledges that expert judgement-based approaches may introduce certain subjective biases due to differences in professional experience, regional exposure, and familiarity with school retrofit projects. In addition, the respondents were not specifically categorised according to urban or rural school locations, which may influence their perception of retrofit priorities.

RESULTS AND DISCUSSION

The RII analysis of the 56 retrofit measures, grouped within the domains of EE, IE, and SO, provided an evidence-based view of expert priorities for retrofitting Malaysian school buildings (Duraivel & Natarajan, 2025). The measures were evaluated by 52 energy auditors, all of whom possessed cross-disciplinary expertise and direct experience in dealing with the performance of tropical buildings (Tang et al. 2024). Their ratings, based on climatic suitability, cost feasibility, and performance impact, revealed clear trends in what industry professionals believed were the most impactful and implementable interventions in the context of public schools.

Table 4 presents the prioritised ranking of the green technology retrofit measures based on the RII values derived from the expert evaluations. To improve the interpretation of the ranking results, the retrofit measures were further categorised into high, medium, and low priority levels, according to their respective RII values, where RII ≥ 0.800 indicated high priority, RII of between 0.600–0.799 indicated medium priority, and RII < 0.600 indicated low priority, following commonly applied RII interpretation approaches in construction management studies (Gündüz et al. 2013). To improve the visual interpretation of the ranking results, the retrofit measures in Table 4 were further differentiated using a shaded priority categorisation.

TABLE 4. The green technology retrofit measures for school buildings

Code	Measure Description	RII	Priority Level
	Energy Efficiency (EE)		
EE-HVAC-02	Sealing and maintenance of ductwork	0.896	High
EE-LIT-04	Installation of energy-saving LED bulbs	0.892	High
EE-HVAC-06	Scheduling regular HVAC maintenance	0.881	High
EE-FAN-02	Installation of on/off motion sensors for fans	0.869	High
EE-HVAC-03	Installation of fan speed controls (HVAC)	0.865	High
EE-FAN-01	Installation of ENERGY STAR-certified fans	0.862	High
EE-HVAC-05	Installation of temperature and humidity controls	0.850	High
EE-LEX-04	Replacement of external standard bulbs with LED bulbs	0.838	High
EE-LIT-01	Installation of occupancy-based light sensors	0.815	High
EE-LIT-03	Assessment of lighting quantity	0.792	Medium
EE-LEX-02	Installation of lighting timers	0.777	Medium
EE-HVAC-01	Installation of airside economiser	0.769	Medium
EE-FAN-04	Replacement of AC motors with electronically-commutated fans	0.762	Medium
EE-LIT-02	Designing of task-specific illumination	0.750	Medium
EE-LIT-05	Set up of lighting zones and controls	0.738	Medium
EE-LEX-03	Determination of lighting fixture placement for optimal luminance	0.662	Medium
EE-LIT-06	Adjustment of colour temperature	0.619	Medium
EE-LEX-01	Dimmers	0.585	Low
	Indoor Environmental Quality (IE)		
IE-ROF-02	Application of reflective roof coating	0.842	High
IE-WIN-05	Improvement of window seals	0.835	High
IE-CEI-02	Installation of ENERGY STAR-certified ceiling fans	0.823	High
IE-WAL-03	Installation of wall shading element	0.812	High
IE-WIN-04	Installation of Venetian blinds	0.804	High
IE-ROF-04	Application of light-coloured roof paint	0.800	High
IE-FAC-02	Installation of high-performance façade elements	0.765	Medium
IE-WAL-02	Improvement of internal wall insulation	0.746	Medium

continue...

...cont.

IE-WIN-02	Application of solar film	0.742	Medium
IE-FAC-03	Proper material selection	0.738	Medium
IE-WAL-01	Improvement of external wall insulation	0.735	Medium
IE-ROF-01	Improvement of roof insulation	0.731	Medium
IE-FAC-01	Improvement of façade insulation	0.731	Medium
IE-FAC-04	Improvement of glazing systems	0.723	Medium
IE-ROF-03	Replacement of roof materials	0.723	Medium
IE-WIN-03	Increasing of window-to-wall ratio	0.719	Medium
IE-WIN-07	Installation of window overhangs/shading	0.712	Medium
IE-CEI-03	Replacement of ceiling with phase change material panels	0.669	Medium
IE-FLR-02	Installation of thermal-efficient finishes	0.638	Medium
IE-CEI-04	Application of reflective ceiling paint	0.615	Medium
IE-FLR-04	Application of reflective floor coating	0.611	Medium
IE-WAL-04	Installation of radiant wall cooling	0.573	Low
IE-WIN-06	Application of gas-filled glazing	0.569	Low
IE-FLR-01	Improvement of airtight floor insulation	0.592	Low
IE-FLR-03	Installation of radiant floor cooling	0.542	Low
IE-FAC-05	Installation of double-skin façade	0.581	Low
IE-CEI-05	Installation of radiant cooling ceiling panels	0.527	Low
	Smart Operational Controls (SO)		
SO-ENG-02	Installation of energy sub-meters	0.827	High
SO-ENG-03	Management of appliance inventory	0.800	High
SO-ENG-05	Installation of intelligent control systems	0.708	Medium
SO-ENG-01	Development of carbon footprint strategies	0.692	Medium
SO-WAT-03	Installation of ENERGY STAR-certified water heaters	0.611	Medium
SO-WAT-01	Installation of water sub-meters	0.538	Low
SO-ENG-04	Installation of electricity-based backup generators	0.535	Low

ENERGY EFFICIENCY (EE)

Within the EE domain, the focus was firmly on mechanical cooling and lighting systems, reflecting their status as the two largest contributors to electricity consumption in schools, often accounting together for more than 70% of total energy use. The dominance of the EE measures demonstrated that operational energy reduction remains the primary concern in Malaysian school retrofits due to the significant electricity consumption associated with cooling and lighting systems. Measures such as sealing and maintaining ductworks (RII = 0.896), installing LED lighting (0.892), and conducting scheduled HVAC maintenance (0.881) ranked the highest.

This prioritisation highlights the importance of tackling systemic energy losses, replacing outdated lighting technology with low-wattage, long-life solutions and ensuring that existing equipment is maintained at peak efficiency. Similar retrofit practices involving LED lighting upgrades, HVAC optimisation, and passive cooling improvements have also been increasingly adopted in Malaysian educational and public-sector buildings to improve operational energy performance and support broader sustainability initiatives.

Other high-priority EE measures, including sensor-based fan controls, fan speed regulation, and the installation of ENERGY STAR-certified fan systems, reinforce the value of adaptive ventilation strategies, especially in school buildings where occupancy levels fluctuate throughout the day. Medium-priority EE measures, such as lighting timers, task-specific illumination, and airside economisers, are technically viable but have a more situational impact, requiring targeted application and, in some cases, advanced humidity management in Malaysia's hot and humid climate. The lower priority given to dimmers and similar manual controls suggests that stakeholders prefer automation and passive control solutions that do not rely on user engagement for energy savings.

Although this study primarily adopted an expert-based prioritisation approach, several high-priority retrofit measures identified in this research have also demonstrated positive performance outcomes in previous studies. For instance, LED lighting retrofits have been reported to reduce lighting-related energy consumption by approximately 40–60% (Dineshkumar, 2013), while reflective roof coatings contribute to lower indoor cooling loads and improved thermal performance in tropical buildings (Jin et al. 2018). Similarly, scheduled HVAC maintenance and duct sealing practices have been associated with improved operational efficiency and reduced energy losses in educational and public-sector facilities. Previous studies have also shown that occupancy sensor systems and lighting timers are effective in reducing unnecessary electricity consumption in intermittently occupied spaces such as classrooms and administrative areas (Rijal et al. 2023).

In addition, energy-efficient ceiling fan systems have been reported to achieve energy savings of approximately 40–50% compared to conventional fan systems, particularly in large educational buildings with high-density fan usage (Nakul et al. 2012). Furthermore, improved window sealing, shading devices, and solar film applications have been recognised for reducing solar heat gain and uncontrolled air infiltration, thereby enhancing indoor thermal comfort in hot and humid climates (Song et al. 2021). Large-scale school retrofit studies have also demonstrated substantial energy-saving potential, with previous research reporting overall reductions ranging from 49–81% following the implementation of integrated energy retrofit strategies in educational buildings (Be'cirovi'c & Vasi'c, 2013; Dall'O et al. 2013). Nevertheless, further empirical validation through a pilot retrofit implementation, post-retrofit performance assessment, or building energy simulation modelling is recommended to strengthen the practical applicability of the proposed prioritisation approach within the Malaysian school environment.

INDOOR ENVIRONMENTAL QUALITY (IE)

In the IE domain, priority was given to passive design enhancements that lower heat gain, improve ventilation, and enhance comfort, thereby reducing the reliance on mechanical cooling. The IE measures were prioritised mainly for their ability to improve thermal comfort, while simultaneously reducing the cooling demand within tropical school environments. Reflective roof coatings (RII = 0.842), improved window seals (0.835), ENERGY STAR-certified ceiling fans (0.823), wall shading elements (0.812), and venetian blinds (0.804) were all rated highly, demonstrating the strong support for measures that reduce solar ingress and draughts, while improving the physical learning environment. Light-coloured roof paints and similar roof surface treatments offer comparable benefits to reflective coatings but are faster to implement and less disruptive.

Medium-priority IE measures, including high-performance façade elements, internal wall insulation, and the application of solar films, have demonstrated technical merit but entail higher costs and more complex installation requirements, making them better suited to a phased implementation. Meanwhile, low-priority IE measures such as radiant cooling technologies, gas-filled glazing, and double-skin façades, while effective in certain high-budget contexts, are generally unsuitable for retrofitting Malaysian public schools due to their cost, complexity, and compatibility with existing structures.

SMART OPERATIONAL CONTROLS (SO)

The SO domain underscored the enabling role of monitoring, automation, and management in sustaining EE and IE gains. Smart operational controls (SO) are recognised as supporting mechanisms that sustain long-term retrofit performance through monitoring and operational optimisation. Installing energy sub-meters (RII = 0.827) and actively managing appliance inventories (0.800) were recognised as high-impact interventions that empower administrators to track consumption and eliminate unnecessary electrical loads. Medium-priority measures, including intelligent control systems and carbon footprint tracking, offer strategic benefits but typically require more institutional commitment and specific staff training for effective operation. Low-priority SO measures, such as water sub-meters and backup generators, provide resilience and resource oversight but have a limited effect on daily energy savings in normal operating conditions.

Across all three domains, the high-priority measures shared three defining features: broad applicability to a variety of school types, low-to-medium implementation cost, and the capacity to deliver immediate and verifiable performance benefits. The EE measures dominated the top of the ranking, reinforcing their central role in school retrofits, while the IE measures complemented them by enhancing building comfort and reducing cooling demand through passive means. The SO measures, although fewer in number, ensured that the EE and IE interventions achieved and maintained their intended impact over time. The medium-priority measures represented opportunities for gradual adoption as funds permitted, while the low-priority measures should be approached selectively and be reserved for pilot projects or for circumstances where specific building conditions justify their cost.

The prioritisation trends identified in this study differed from the findings reported in several international retrofit studies, where advanced façade systems, radiant cooling technologies, and double-skin façades were often prioritised due to their long-term energy performance benefits (Heracleous et al. 2021; Kaczmarek, 2025). In contrast, the Malaysian respondents demonstrated a stronger preference for low-cost and operationally practical interventions such as duct sealing, LED retrofits, reflective roof coatings, and scheduled HVAC maintenance. This variation reflected the financial limitations, maintenance constraints, and ageing infrastructure conditions commonly faced by Malaysian public schools. The findings indicated that retrofit decision-making in tropical public educational facilities is influenced not only by their theoretical energy-saving potential but also by their implementation practicality, maintenance capability, and institutional affordability.

Although this study primarily focused on prioritising retrofit interventions based on expert judgement, climatic suitability, and operational practicality, cost considerations remain an important aspect in real-world retrofit implementation. In this study, several high-priority measures, such as LED retrofits, duct sealing, and reflective roof coatings, were perceived by the experts as practical interventions due to their relatively straightforward implementation and operational benefits. Future studies may further explore detailed cost-benefit or lifecycle cost assessments to complement the proposed prioritisation framework.

These findings have direct implications for policy and practice. At the policy level, the Ministry of Education and national retrofit programmes should give precedence to low-cost, high-impact measures during initial retrofit phases, notably duct sealing, LED lighting upgrades, scheduled HVAC servicing, reflective roof coatings, window seal enhancements, and energy sub-meter installations. Such actions are scalable across the national school network, deliver fast returns on investment, and can be implemented with minimal interference to school operations.

Sequencing is critical for practitioners. More specifically, adopting quick-win EE and IE measures first builds momentum and produces tangible results that can support applications for further funding. Embedding SO interventions at an early stage is important to ensure continuous monitoring and sustained savings. Ultimately, this prioritisation approach helps bridge the gap between broad sustainability objectives and the operational realities of Malaysian school retrofits. By integrating the consensus of experts with a structured RII analysis, it equips stakeholders with a clear roadmap for selecting interventions that maximise performance given the available resources, while enabling a flexible, phased planning for the ongoing modernisation of schools.

CONCLUSION

This study set out to address the challenge of selecting appropriate green technology retrofit measures for Malaysian school buildings by developing a prioritisation methodology grounded in established sustainable building theory and tailored to the local hot and humid climate. Through an extensive literature review, measures were categorised into three domains, namely, EE, IE, and SO, reflecting both international best practices and the operational realities of Malaysian schools.

The assessment of these interventions by 52 energy auditors, using criteria such as climatic appropriateness, cost-effectiveness, and performance impact, allowed for the application of the RII to produce a clear, evidence-based ranking. The findings highlighted a strong agreement on the significance of high-priority interventions, including duct sealing, LED lighting upgrades, scheduled HVAC maintenance, and sensor-based fan controls within the EE domain. Similarly, reflective roof coatings, improved window seals, and shading elements were highly valued in the IE domain, while energy sub-metering and appliance inventory management stood out in the SO domain.

Medium-priority measures generally require higher investments or are more context-specific, while low-priority measures involve specialised technologies with limited applicability for typical Malaysian public school retrofits. Overall, the findings demonstrate that the proposed prioritisation approach can assist stakeholders in identifying retrofit interventions that balance performance, practicality, and climatic suitability within resource-constrained school environments.

From a theoretical perspective, this study contributes to the sustainable retrofit literature by integrating EE, IE, and SO within a unified retrofit prioritisation approach for tropical school buildings. Methodologically, the study demonstrates how an expert-based RII analysis can be applied to support climate-responsive retrofit decision-making within resource-constrained public educational environments.

Organising these priorities within a clear domain-based structure allows the methodology to function as a practical, evidence-driven decision-support tool for policymakers, school administrators and practitioners seeking to plan sustainable school upgrades. It promotes targeted resource allocation towards measures that maximise efficiency, comfort, and operational sustainability and outlines a phased pathway for implementation. Furthermore, the methodology is adaptable across various regional contexts and building types, with the potential to be integrated into broader educational infrastructure planning and national sustainability initiatives.

Although the framework was specifically developed for Malaysian public school buildings within a hot and humid tropical climate, the overall prioritisation approach may also be adapted for other public building categories such as universities, offices, and healthcare facilities. However, the prioritisation criteria and retrofit measures may need to be adjusted to local climatic conditions, operational requirements, and resource availability in different regional contexts.

The proposed prioritisation approach may also assist policymakers and school facility managers in identifying retrofit interventions that are technically feasible, operationally practical, and adaptable to resource-constrained educational environments.

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DECLARATION OF COMPETING INTEREST

None.

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