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TOWARDS A SUSTAINABLE DESIGN FRAMEWORK FOR BIOMEDICAL RESEARCH FACILITIES: INTEGRATING ENERGY EFFICIENCY AND CONTEXT-RESPONSIVE DESIGN

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ABSTRACT

Biomedical research facilities are among the most energy-intensive building types due to their stringent ventilation, thermal control, biosafety, equipment, and operational requirements. In resource-constrained contexts such as Nigeria, these demands are further complicated by unreliable electricity supply, limited technical capacity, and the need for context-appropriate design solutions. This study examines how energy efficiency and contextual responsiveness can be integrated into the design of biomedical research facilities. A comparative case study approach was adopted, supported by literature and documentary review. Five biomedical research facilities in Nigeria, Australia, and the United States were purposively selected to reflect differences in climate, infrastructure, and institutional capacity. The cases were assessed using criteria covering functional and spatial organisation, energy efficiency, climate responsiveness, resource efficiency, environmental performance, flexibility, and operational resilience. Cross-case analysis was used to identify common, context-dependent, and transferable design strategies. The findings show that sustainable performance is strongest where functional planning, passive design, energy systems, resource management, and operational considerations are integrated rather than treated independently. Key strategies identified include functional zoning, climate-responsive orientation, controlled day lighting, high-performance envelopes, zoned mechanical systems, renewable energy generation, water and waste management, and adaptable planning. The analysis also revealed important tensions between energy efficiency and ventilation, natural ventilation and biosafety, daylighting and environmental control, flexibility and fixed services, and advanced technology and maintenance capacity. The study proposes a five-dimension sustainable design framework comprising Functional Efficiency, Energy Efficiency, Climate and Environmental Responsiveness, Resource Efficiency, and Operational Resilience. The framework provides a context-responsive basis for designing biomedical research facilities that are energy-efficient, operationally reliable, adaptable, and suitable for differing climatic and infrastructural conditions.

Keywords: Biomedical research facilities; Sustainable design; Energy efficiency; Climate-responsive design; Resource efficiency; Operational resilience; Context-responsive design

1. Introduction

1.1 Background

Biomedical research facilities are a combination of improvement in science and architectural complexity. As laboratories become increasingly central to disease monitoring or tracking, diagnostics, drug development, genomics, and public health innovation, the buildings that support this work must accommodate highly specialized functions while consuming substantial amounts of energy and resources. Unlike conventional institutional buildings, biomedical research facilities operate within demanding environmental and technical conditions, requiring controlled ventilation, thermal stability, specialised equipment, strict biosafety measures, and reliable building services. Biomedical research infrastructure has grown in importance over the last two decades, driven by repeated epidemic and pandemic threats, the expansion of biomedical research and translational medicine and the recognition that national health security depends on domestic research capacity rather than dependence on external laboratories (Meder et al., 2016, Okonofua et al., 2022). Biomedical research institutes are not conventional institutional buildings, they combine wet and dry laboratories, biosafety-level containment suites, cold storage and biorepositories, computational and data-analysis facilities, and clinical or training functions within a single, tightly serviced envelope (Sreepadmanabh et al., 2020, Madhu et al., 2022). This specialisation carries direct architectural and environmental consequences which include laboratory spaces demanding a controlled ventilation and pressure regimes, biosafety suites demanding containment and access control, and cold storage and analytical equipment demand uninterrupted power and precise thermal stability (Gao et al., 2025, Carranza et al., 2025).

The energy consequence of this specialisation is severe. According to Saini et al.(2022), Buildings account for roughly a third of global energy consumption and around 40% of global electricity use, and within that footprint, laboratory and research typologies are disproportionately energy-intensive, continuous air-change requirements, dense equipment loads (ultra-low-temperature freezers, centrifuges, fume hoods, autoclaves), and 24-hour operational demand routinely push biomedical facilities to consume several times the energy per square metre of a standard commercial or educational building (Leal Filho et al., 2019, Cheng et al., 2024, Alnahhal et al., 2024). HVAC alone typically dominates this profile, compounded by lighting, laboratory equipment, and the backup power infrastructure needed to guarantee continuity (Aledhari et al., 2022, Jovičić & Milinković, 2025).

Sustainability challenges surrounding this building type are sharper still in developing contexts. In Nigeria, as in much of the Global South, unreliable grid electricity, heavy reliance on diesel generators, ageing HVAC infrastructure, and limited local technical capacity to install or maintain advanced systems combine to make energy-intensive research infrastructure both operationally fragile and environmentally costly (Mu'azu, 2015, Isah et al., 2024, Onuh et al., 2024). Where energy efficiency has been embedded into institutional building design in developed economies, it remains largely absent from Nigerian design and operational practice, despite the country's own national and global climate commitments (Umeh et al., 2024).

Three interlinked problems define the design challenge this article addresses. First, conventional architectural practice tends to treat energy efficiency as a downstream technical problem to be resolved by mechanical and electrical engineers after the building's form, orientation, and spatial organisation have already been fixed, rather than as an integrated architectural consideration from the earliest design stages (Hafez et al., 2023, Benitez et al.,

2019). This sequencing forecloses many of the cheapest and most durable efficiency gains, which depend on decisions, massing, orientation, zoning made before a mechanical engineer is typically involved.

Second, biomedical facilities must satisfy function, biosafety, environmental control, energy performance, and operational requirements simultaneously, and these requirements are frequently in direct tension. Passive strategies that reduce energy demand in ordinary buildings operable windows, cross-ventilation, daylight-led massing are constrained or foreclosed altogether in core laboratory zones by containment and pressure-differential requirements (Kwong et al., 2019, Ahmed et al., 2019).

Thirdly, advanced solutions developed in stable, well-resourced, temperate-climate contexts are not automatically transferable to different climatic, infrastructural, and economic conditions. A highly glazed, mechanically dominant, digitally controlled facility designed for a stable European or North American grid cannot simply be exported to a context with intermittent electricity supply, higher ambient humidity, and a thinner pool of specialist maintenance technicians (Gerarden et al., 2017, Ochedi & Taki, 2019).

A substantial literature already exists on sustainable laboratory design and energy-efficient buildings more broadly, but there is a dearth in knowledge that explicitly connects biomedical functional requirements, energy efficiency, climate responsiveness, resource efficiency, adaptability, and contextual constraints, treating these dimensions as interdependent rather than as separate technical checklists to be satisfied in isolation. Much of the empirical evidence on laboratory energy performance is drawn from grid-stable, well-funded contexts (Gerarden et al., 2017, US DOE, 2026), and the relatively small body of work on Nigerian institutional energy performance addresses hospitals, schools, and residential buildings rather than purpose-built biomedical research facilities (Okonta, 2023, Saleh et al., 2023). This leaves a clear gap, there is a dearth in knowledge on the framework that connects biomedical-specific functional and biosafety requirements to energy efficiency strategy in a way that is explicitly adapted to resource-constrained, climatically demanding contexts. This study therefore develops a sustainable design framework for biomedical research facilities that integrates energy efficiency with context-responsive architectural strategies, built from a comparative analysis of five biomedical research facilities spanning three countries and three distinct climatic and infrastructural contexts.

2. Sustainable Design Requirements of Biomedical Research Facilities

In 21st century, Sustainability is one of the important concepts. According to Abdeen (2008) sustainability is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

2.1 Functional and Spatial Requirements

i. Laboratory zoning**.** Biomedical facilities require clear separation between wet laboratories (chemical and biological experimentation), dry laboratories (computational and bioinformatics work), tissue-culture and sample-preparation rooms, cold storage and biorepositories, and mechanical/equipment rooms (Joshi et al., 2025, Mukherjee et al., 2023). Each zone carries distinct environmental tolerances, and zoning failures mixing high- and low-sensitivity functions without adequate separation compromise both research integrity and energy performance.

ii. Functional relationships**:** The adjacency between laboratories, support spaces, and administrative or collaborative areas shapes both workflow efficiency and contamination risk. Zhang et al.(2020) sated that Poorly considered functional relationships increase unnecessary movement of biological materials and researchers between zones of differing biosafety sensitivity

iii. Circulation**:** Separate circulation for laboratory materials, general staff, and public visitors is a recurring requirement, both for biosafety and for operational efficiency (Gericke et al., 2022).

iv. Support spaces: Administrative offices, meeting and training rooms, cafeterias, and library or collaborative spaces sit alongside the technical core and must be planned so they do not compromise the security or environmental stability of laboratory zones.

v. Flexibility and expansion. Because biomedical research technologies and priorities evolve quickly, modular laboratory planning and flexible infrastructure service risers, expandable floor plates, non-load-bearing partitions are widely identified as necessary to avoid premature obsolescence (Atef et al., 2024, Mostafavi, 2022).

2.2 Environmental and Biosafety Requirements

Ventilation. Continuous, often single-pass (non-recirculated) ventilation is required in many laboratory zones, driving substantially higher air-change rates than in conventional buildings (Gao et al., 2025).

Air quality. Filtration standards, fume-hood exhaust, and control of particulates and biological aerosols are governed by the biosafety level of the space in question.

Thermal control. Precise temperature and humidity tolerances are required to protect samples, reagents, and sensitive equipment, and to maintain researcher comfort during extended laboratory sessions.

Containment. Physical and procedural containment sealed envelopes, airlocks, directional airflow scales with biosafety level, from minimal requirements at BSL-1 to full positive-pressure suits and highly restricted access at BSL-4 (WHO, 2020, Gao et al., 2024).

Pressure relationships. Directional, negative-pressure airflow prevents the escape of contaminated air from higher-risk zones, this requirement directly conflicts with natural ventilation strategies in and around core laboratory spaces (Ahmad, 2021).

Safety. Beyond biosafety proper, general life-safety requirements fire protection, emergency egress, chemical and biological waste handling apply throughout.

2.3 Energy and Resource Requirements

HVAC energy. Typically the single largest energy consumer in this typology, driven by continuous conditioning and high air-change rates (Meyn et al., 2023).

Lighting. Laboratory and support-space lighting must balance illumination adequacy against energy demand, with daylighting playing a variable role depending on space sensitivity.

Laboratory equipment. Ultra-low-temperature freezers, centrifuges, autoclaves, and fume hoods impose continuous, often high intensity loads independent of occupancy (Odunayo, 2024).

Water. Laboratory processes, autoclaving, and general sanitary demand require reliable water supply and, increasingly, water-efficient fixtures and reuse strategies.

Waste. Biomedical, chemical, and general waste streams require segregated handling, storage, and disposal infrastructure, with implications for both space planning and operational cost.

Materials. Material specification affects thermal performance, contamination control (through surface porosity and jointing), and lifecycle maintenance burden (Sayers, 2021).

3. Methodology

3.1 Research Approach

This study adopts comparative case-study research, supported by literature and documentary review, following a qualitative and inductive approach appropriate to generating contextually grounded design

3.2 Case Study Selection

Five biomedical research facilities were purposively selected to capture variation in climate, grid reliability, and institutional resourcing:

1. Institute of Genomics and Global Health, Ede, Nigeria
2. Institute of Human Virology Nigeria, Abuja, Nigeria
3. Institute of Advanced Medical Research and Training, Ibadan, Nigeria
4. Flinders University Health and Medical Research Building, Adelaide, Australia
5. Ragon Institute, Cambridge, Massachusetts, USA

3.3 Analytical Framework

Each facility was evaluated against a single, consistent set of criteria, summarised in Table 1.

Table 1: Analytical Framework Applied to Each Case Study

Criterion	**What Is Assessed**
Functional/spatial organisation	Zoning, adjacency, circulation, flexibility for future expansion
Energy efficiency	Orientation, envelope, HVAC strategy, lighting, renewable energy, energy management systems
Climate responsiveness	Passive design strategy relative to local climate and solar conditions
Water/resource efficiency	Water management, waste management, material selection
Environmental performance	Indoor environmental quality, daylighting, thermal comfort
Flexibility/adaptability	Capacity for future reconfiguration or expansion
Operational considerations	Maintenance burden, technical capacity required, infrastructure reliability dependence

4. Comparative Analysis of Biomedical Research Facilities

4.1 Functional and Spatial Strategies

Zoning. All five facilities incorporate functional zoning, although its application varies with scale and context. The Institute of Genomics and Global Health, Ede, separates laboratory and administrative areas while using open-plan layouts to support airflow and reduce unnecessary cooling. The Institute of Human Virology Nigeria, Abuja, adopts a clearer separation through independent research and administrative towers, allowing mechanical systems to respond to different operational demands. Flinders University Health and Medical Research Building organizes its ten floors according to laboratory, office, and flexible workspace functions. The Ragon Institute similarly separates high-energy laboratory areas from lower-energy support spaces. In contrast, the Institute of Advanced Medical Research and Training exhibits weaker functional zoning, as its spatial organization reflects a general institutional layout rather than laboratory-specific requirements.

Circulation. Institute of Human Virology Nigeria, Abuja's inclusion of a dedicated laboratory service lift, separate from general circulation, exemplifies good practice in separating sensitive material movement from staff and visitor traffic. Flinders University Health and Medical Research Building and Ragon both use central atria and interconnecting stairs to promote interdisciplinary interaction while keeping laboratory circulation contained and legible. Institute of Advanced Medical Research and Training's linear circulation pattern is explicitly identified as restricting interaction and producing poor flow.

Laboratory organization; The Institute of Genomics and Global Health, Ede, and the Institute of Advanced Medical Research and Training both use courtyards to organize laboratory and office spaces. However, the former integrates this arrangement with modern biosafety infrastructure, while the latter has no dedicated BSL laboratory provision. The Ragon Institute demonstrates the strongest energy-based zoning, deliberately separating high-intensity laboratory spaces from lower-load administrative areas to improve mechanical efficiency.

Flexibility and expansion: In flinders university health and medical research building's service, while efficient in day-to-day operation, are noted in the case material as a constraint on future retrofit reconfiguring gas, power, or data distribution embedded in a fixed spine is comparatively difficult and costly. Institute of Genomics and Global health, Ede's Phase 1 construction status suggests a facility still being expanded incrementally. Institute of Advanced Medical Research and Training shows essentially no capacity for flexible reconfiguration, being a repurposed rather than a modularly planned building.

4.2 Energy-Efficient Design Strategies

Orientation: The Institute of Advanced Medical Research and Training is oriented along the east–west axis to limit solar heat gain and respond to prevailing winds, supporting passive ventilation. Ragon's curved and cantilevered form responds to solar exposure within its triangular site. Similarly, the Flinders University Health and Medical Research Building uses facade orientation to reduce solar gain while improving daylight and natural ventilation.

Daylightingng: Flinders University Health and Medical Research Building uses floor-to-ceiling glazing and winter gardens to provide daylight and external views. Ragon combines extensive glazing with triple-glazed curtain walls to improve daylight while controlling heat gain. The Institute of Genomics and Global Health, Ede, uses double-glazed facades to

increase daylight and limit heat penetration, while the Institute of Human Virology Nigeria, Abuja, combines large glazed areas in administrative spaces with tinted glazing in laboratories. The Institute of Advanced Medical Research and Training relies mainly on daylight from its central courtyard, with limited deliberate glazing strategies.

Solar shading: Ragon employs parametrically modelled external shading devices that respond dynamically to solar angle. Flinders University Health and Medical Research Building uses automated louvre systems that adjust to sun position and climatic conditions. Institute of Advanced Medical Research and Training includes only basic horizontal shading devices, applied without the responsiveness seen in the two international cases.

Building envelope: The Institute of Genomics and Global Health, Ede, combines rammed-earth walls, insulation, and double glazing to provide thermal mass and reduce temperature fluctuations. Flinders University Health and Medical Research Building uses high-performance glazing that limits solar heat gain. Ragon incorporates a low-carbon timber curtain wall with triple glazing to address both operational and embodied carbon. The Institute of Human Virology Nigeria, Abuja, uses tinted laboratory glazing as a simpler solar-control measure. In contrast, the Institute of Advanced Medical Research and Training uses a conventional concrete-block envelope selected mainly for cost and availability, with limited insulation and no high-performance glazing.

HVAC: Ragon's optimised airflow strategy avoids excess air-change rates beyond regulatory requirements, a deliberate departure from the conservative ventilation defaults common in laboratory design. Flinders University Health and Medical Research Building pairs high - performance glazing with zoned mechanical systems calibrated to differentiated laboratory and office demand. Institute of Genomics and Global health, Ede's building management system dynamically prioritises cooling and ventilation load toward mission-critical zones (biorepositories, cold rooms) ahead of lower-priority spaces. Institute of Human Virology Nigeria, Abuja and Institute of Advanced Medical Research and Training both show more conventional, less zoned hvac provision, with Institute of Advanced Medical Research and Training lacking any smart hvac control.

Lighting: All facilities except Institute of Advanced Medical Research and Training show deliberate led and daylight-integrated lighting strategy, Institute of Advanced Medical Research and Training relies on artificial lighting without daylight-responsive control outside its courtyard-adjacent spaces.

Renewable energy: Flinders University Health and Medical Research Building operates entirely on renewable electricity from on-campus solar photovoltaics and contracted wind power. The Institute of Genomics and Global Health, Ede, uses an on-site solar farm designed to support continuous laboratory operations. The Institute of Human Virology Nigeria, Abuja, also incorporates a 300 kWp photovoltaic system, reducing reliance on the grid. Ragon is designed to be all-electric-ready but has limited on-site renewable generation, while the Institute of Advanced Medical Research and Training has no dedicated renewable-energy system and relies partly on wider University of Ibadan photovoltaic deployment.

Energy management: The Institute of Genomics and Global Health, Ede, has the most advanced building management system among the Nigerian cases, integrating cooling, ventilation, lighting, and power monitoring. Flinders University Health and Medical Research Building and Ragon similarly use automated, sensor-based controls. The Institute of Human Virology Nigeria, Abuja, has photovoltaic generation but lacks dedicated monitoring for load

matching and performance assessment. The Institute of Advanced Medical Research and Training has no building management system.

4.3 Resource and Environmental Strategies

Water management: The Institute of Advanced Medical Research and Training uses permeable surfaces and natural drainage for stormwater management, a strategy also applied at the Institute of Genomics and Global Health, Ede. In contrast, the Institute of Human Virology Nigeria, Abuja, has limited water-efficiency measures. Ragon and Flinders University Health and Medical Research Building incorporate more integrated water-management strategies, including bioswales and site drainage systems.

Waste management: Biomedical, chemical, and general waste management are incorporated into the proposed Lagos facility through waste segregation, dedicated service circulation, and controlled storage. Among the case studies, the Institute of Human Virology Nigeria, Abuja, and the Institute of Genomics and Global Health, Ede, provide the clearest waste-handling provisions for biomedical operations. The Institute of Advanced Medical Research and Training, however, lacks dedicated waste-management infrastructure due to its general-purpose building design.

Materials: Institute of Genomics and Global Health, Ede's rammed-earth and epoxy-floor-finish specification reflects deliberate hygiene and thermal performance selection. Ragon's low-carbon timber curtain wall and "red-list-free" material specification reflect an explicit embodied-carbon and occupant-health agenda. Flinders University Health and Medical Research building's material selection prioritises durability and lifecycle performance consistent with its sustainability certification. Institute of Human Virology Nigeria, Abuja's material choices are functional but less explicitly performance-driven. Institute of Advanced Medical Research and Training's concrete block construction, chosen for cost and availability, actively undermines contamination control due to porosity and poor sealing.

Landscape: Ragon's landscape strategy (reed hilderbrand's "productive ecology" concept, native planting, urban tree canopy) is the most developed of the five, followed by flinders university health and medical research building's biophilic terraces and winter gardens. Institute of Genomics and Global Health, Ede and Institute of Advanced Medical Research and Training both use landscaping for microclimate moderation and shading, though at a more modest technical level. Institute of Human Virology Nigeria, Abuja's landscaping addresses noise buffering and stormwater management alongside aesthetic and psychological comfort goals for staff.

Indoor environmental quality: Flinders University Health and Medical Research Building and Ragon both show strong daylighting-driven ieq strategy, supported by acoustic treatment (wooden ceilings at both). Institute of Genomics and Global Health, Ede's biophilic integration supports occupant wellbeing without additional energy cost. Institute of Advanced Medical Research and Training's hard-surfaced construction is explicitly identified as producing poor acoustic performance, undermining concentration in adjacent research spaces.

4.4 Context-Responsive Strategies

Climatic response; The Institute of Genomics and Global Health, Ede, and the Institute of Advanced Medical Research and Training use courtyard forms to promote daylighting and cross-ventilation, responding to Nigeria's tropical climate. In contrast, Flinders University Health and Medical Research Building and Ragon rely more on airtight envelopes and

controlled mechanical ventilation, reflecting the climatic conditions of their respective locations.

Energy reliability: Energy reliability marks a major difference between the Nigerian and international cases. The Institute of Genomics and Global Health, Ede, sizes its solar farm around limited grid availability, while the Institute of Human Virology Nigeria, Abuja, uses a carport-mounted photovoltaic system to address similar supply constraints. In contrast, Flinders University Health and Medical Research Building and Ragon are less dependent on renewable energy for operational continuity, with their systems primarily supporting decarbonisation goals.

Water infrastructure: Nigerian facilities generally show greater reliance on on-site drainage and passive water management, reflecting less consistent municipal infrastructure, though this is addressed unevenly and is not as developed as the energy-reliability response.

Local materials: Institute of Genomics and Global Health, Ede's rammed-earth construction is a direct example of a locally available, thermally effective material chosen partly for its performance in the local climate. Institute of Advanced Medical Research and Training's concrete block construction shows the opposite pattern: a locally available material chosen for cost without regard to laboratory-specific performance needs.

Maintenance: Institute of Human Virology Nigeria, Abuja's absence of energy monitoring infrastructure, despite substantial photovoltaic investment, reflects a broader pattern in which advanced digital systems are more likely to be specified in contexts (flinders university health and medical research building , ragon) where the maintenance capacity to sustain them is assured.

Technological dependence: The two international facilities lean heavily on digital building-management sophistication precisely because that dependence is a safe bet in their operating context, the Nigerian facilities show a more conservative, hedged approach to technology dependence, favouring architectural and passive solutions that continue to function even if digital systems are not consistently maintained.

4.5 Cross-Case Synthesis

Common strategies: Across all five facilities, clear functional zoning by sensitivity and energy demand, separation of laboratory and administrative/public circulation, passive daylighting wherever biosafety constraints allow, and some form of on-site or supplementary renewable generation.

i. **Context-dependent strategies.** From these common foundations, the specific expression diverges by context, heavy mechanical zoning where grid supply is stable (Flinders University Health and Medical Research building, Ragon), courtyard-driven cross-ventilation and thermal buffering where it is not (Institute of Genomics and Global health, Ede, Institute of Advanced Medical Research and Training), and the depth of digital building-management integration tracking available capital and maintenance capacity rather than climate as such.

ii. **Transferable strategies.** From the divergence, several strategies emerge as genuinely transferable regardless of context: passive-first massing and courtyard planning, scalable, zoned mechanical systems that avoid uniform over-conditioning of the entire footprint, and on-site renewable generation explicitly sized against actual, rather than nominal, operational continuity requirements.

5. Towards a Sustainable Design Framework

5.1 Framework Components

Five dimensions, drawn directly from the synthesis, structure the proposed framework:

1. Functional Efficiency: spatial organisation, zoning, circulation, flexibility.

2. Energy Efficiency: passive design, envelope, daylighting, HVAC, lighting, renewable energy.

3. Climate and Environmental Responsiveness: orientation, shading, ventilation, thermal comfort, landscape.

4. Resource Efficiency: water, materials, waste, and lifecycle considerations.

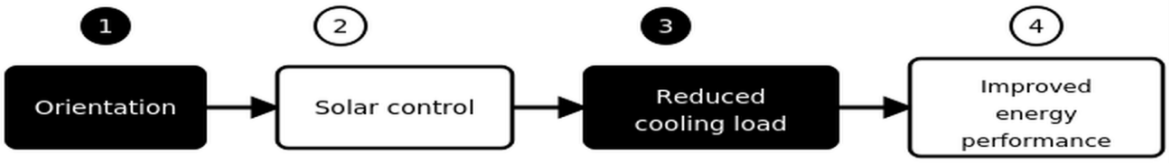
5. Operational Resilience: biosafety, maintenance, infrastructure reliability, adaptability, and future expansion.

These five dimensions represent a practical, design-facing translation of the theoretical position developed through Systems Theory and Bioclimatic Design Theory, previously synthesised as an Integrated Systems–Bioclimatic Energy Performance Framework

5.2 Integration of the Components

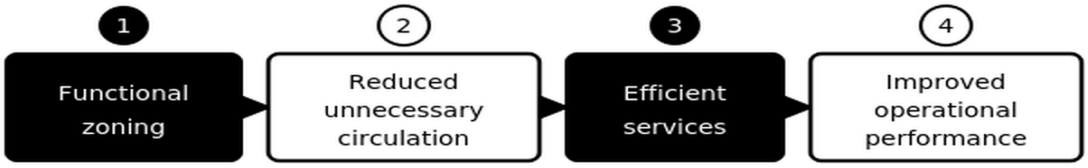
The five dimensions are not independent checklists to be satisfied separately, each functions as a link in a causal chain, where a decision made in one dimension determines what is achievable in the next. Two chains, drawn directly from the case-study evidence, illustrate this:

Chain 1. Climate response to energy performance:



Chain 1 - Climate response to energy performance

Flinders University Health and Medical Research Building's facade orientation and Ragon's parametric shading both exemplify this chain directly: orientation decisions taken at the concept stage determine solar exposure, which determines cooling demand, which in turn determines whether the facility's overall energy performance target is achievable at all.



Chain 2 - Functional planning to operational performance

Institute of Human Virology Nigeria, Abuja's tower separation and Institute of Genomics and Global health, Ede's zone-prioritised Building Management System both exemplify this second chain: grouping Institute of Genomics and Global Health, Ede demand laboratory functions together, rather than scattering them through the plan, reduces unnecessary circulation of both people and services, allows mechanical distribution to be simplified and zoned rather than run uniformly, and ultimately improves the facility's overall operational performance.

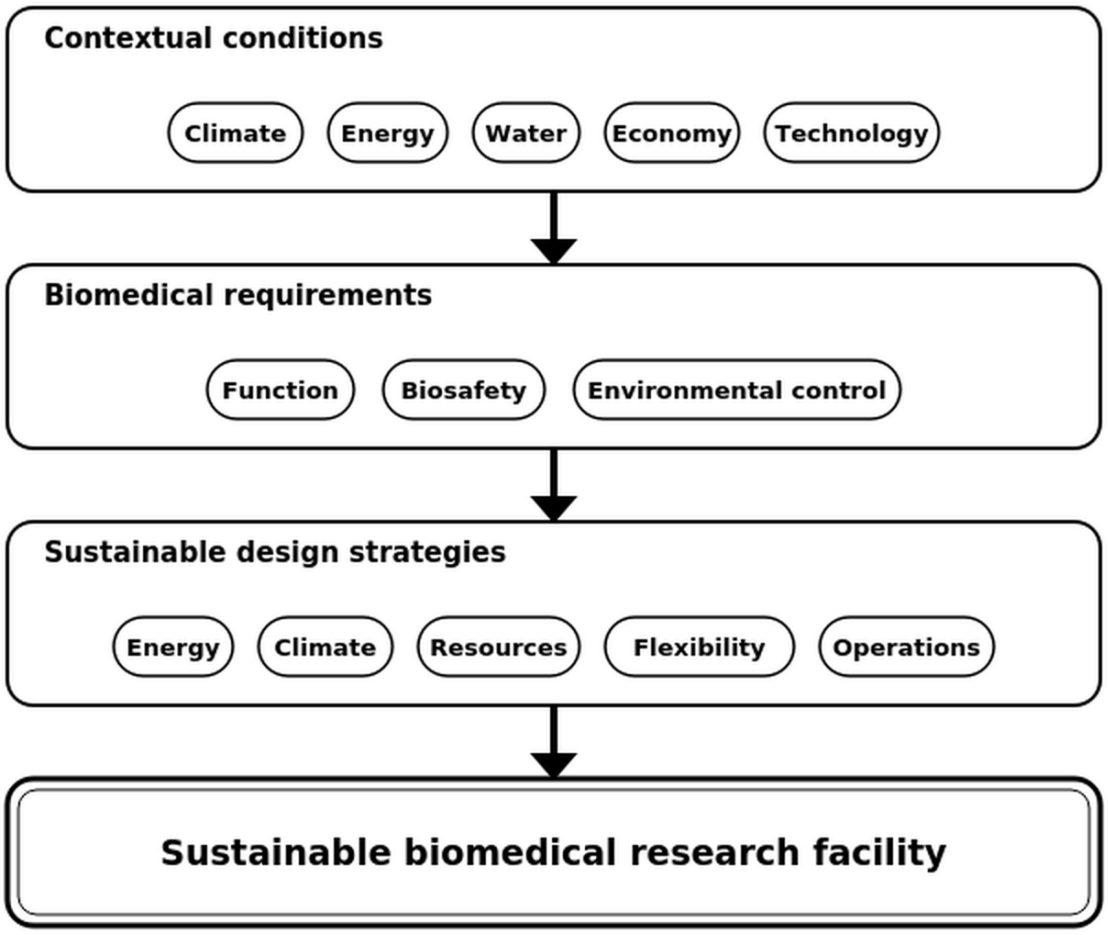
A third chain, evident specifically in the Nigerian cases, is worth naming explicitly given its centrality to the context-responsive contribution of this framework:



Chain 3 - Energy infrastructure to operational resilience

Institute of Genomics and Global Health, Ede's solar farm and Institute of Human Virology Nigeria, Abuja's carport photovoltaic array both demonstrate this chain: recognising grid unreliability as a fixed contextual constraint, rather than treating it as a temporary problem to be solved by more generator capacity, leads directly to renewable generation sized against real operational continuity needs, which in turn reduces both cost and carbon exposure over the facility's lifetime.

5.3 Proposed Framework Mode



6. Discussion

6.1 Beyond Energy Efficiency

The comparative evidence makes it difficult to treat energy efficiency as a sufficient goal in itself. Institute of Advanced Medical Research and Training is, in a narrow sense, passively efficient. Its courtyard genuinely reduces cooling and lighting loads yet it is not a functioning contemporary biomedical research facility. It lacks BSL laboratory provision, environmental monitoring, and any building management system. Energy performance divorced from functional adequacy and biosafety compliance is not a meaningful achievement in this typology, it is, at best, a partial and potentially misleading result.

6.2 Balancing Sustainability and Biomedical Requirements

Five recurring tensions emerge from the case studies, highlighting areas that require careful design resolution.

Energy efficiency vs. ventilation requirements. Laboratory ventilation is a major source of energy demand but remains essential for researcher safety and sample protection. Ragon demonstrates that efficiency can be improved by optimising airflow to required standards rather than over-provisioning systems.

Natural ventilation vs. biosafety. Although operable windows can improve comfort and wellbeing, they may compromise pressure control in containment areas. Their use therefore requires careful zoning and restriction around BSL-related spaces.

Daylighting vs. environmental control. Extensive glazing can improve daylight and occupant experience, but laboratory areas require shading, tinting, and high-performance glazing to limit solar heat gain and maintain stable environmental conditions.

Flexibility vs. fixed services. Centralised service spines, as seen at Flinders, support efficient distribution but may make future changes to gas, power, and data systems more difficult and costly.

Advanced technology vs. maintenance capacity. The limited use of real-time monitoring in the Nigerian cases, despite investment in renewable energy, reflects not only design limitations but also constraints in the availability of technical capacity required to operate and maintain advanced systems effectively (Onuh et al., 2024).

6.3 Context-Responsive Application

The comparative analysis shows that sustainable design cannot be prescribed generically and applied uniformly across contexts. Instead, sustainable strategies should respond to:

i. **Climate:** courtyard- and cross-ventilation-led strategies (Institute of Genomics and Global health, Ede, Institute of Advanced Medical Research and Training) depend on climatic conditions, consistent solar availability and a workable diurnal temperature range, that do not hold everywhere, just as airtight, mechanically dominant strategies (flinders university health and medical research building, Ragon) depend on climatic conditions specific to their own temperate contexts.

ii. **Infrastructure:** a design that assumes continuous grid supply is not merely suboptimal but potentially unworkable in a context of 4–8 hour daily supply, the reverse is also true, in that a facility over-engineered for self-sufficiency in a stable-grid context wastes capital that could be spent elsewhere.

iii. **Available technology:** the depth of digital building-management integration should track what is realistically procurable and serviceable locally, not simply what represents current international best practice.

iv. **Economic capacity:** material and system specification (rammed earth versus low-carbon timber curtain wall, for instance) reflects, and should openly acknowledge, the capital available to a given project rather than aspiring uniformly to the highest-specification precedent.

v. **Maintenance capability:** any system specified must be matched to a realistic assessment of who will maintain it, and how, over the facility's operational lifetime.

6.4 Architectural Implications

The framework carries specific implications for architects at each stage of a biomedical facility project:

Site planning. Energy infrastructure reliability and climate should be surveyed with the same rigour applied to physical site constraints, since they determine which downstream strategies are viable at all.

Concept design. Functional zoning and biosafety adjacency should be resolved before committing to a structural grid or servicing strategy, since retrofitting zoning logic onto an already-fixed structural system (as at Institute of Advanced Medical Research and Training) is far costlier than establishing it from the outset.

Spatial planning. Laboratory, administrative, and support functions should be grouped by energy and biosafety demand rather than by conventional departmental logic, enabling the differentiated mechanical conditioning demonstrated at Institute of Human Virology Nigeria, Abuja and Ragon.

Envelope design. Envelope specification should be treated as inseparable from HVAC and lighting strategy, not as a separate aesthetic or budgetary decision made independently of mechanical engineering input.

Environmental systems integration. Building management and monitoring systems should be specified in proportion to what the facility's operators can realistically sustain over its lifecycle, rather than to a theoretical performance optimum that may not survive first contact with local maintenance capacity.

Lifecycle planning. Flexibility for future reconfiguration modular laboratory units, accessible service risers, expandable floor plates should be built in from the earliest design stages, since biomedical research priorities and technologies will continue to evolve over any facility's operational life.

7. Conclusion

The comparative analysis of five biomedical research facilities across three countries demonstrates that sustainable and energy-efficient design cannot depend on isolated interventions. Rather, performance is achieved through the integration of functional planning, energy systems, climate-responsive design, resource management, and operational resilience from the outset. Sustainable biomedical architecture is therefore best understood as an integrated design process rather than the addition of individual energy-saving measures to a conventional scheme.

The principal contribution of this study is the proposed five-dimension framework, developed from the Integrated Systems–Bioclimatic Energy Performance model. The framework provides architects and institutional planners with a practical basis for balancing competing requirements while recognising context including climate, infrastructure, economic capacity, and maintenance capability as fundamental design considerations. As biomedical research infrastructure expands in resource-constrained settings, particularly across developing regions, this context-responsive approach offers a more appropriate alternative to directly transferring specifications developed for high-resource environments. It provides a pathway towards facilities that can support scientific performance while remaining energy-efficient, adaptable, and operationally sustainable throughout their lifespan.

REFRENCES

Ahmad, P. (2021). *Airborne infection control guide to planning & designing of hospitals.* Jaypee Brothers Medical Publishers.

Ahmed, M. A. A. E. D., & Fikry, M. A. (2019). Impact of glass facades on internal environment of buildings in hot arid zone. *Alexandria Engineering Journal*, *58*(3), 1063–1075.

Aledhari, M., Razzak, R., Qolomany, B., Al-Fuqaha, A., & Saeed, F. (2022). Biomedical IoT: Enabling technologies, architectural elements, challenges, and future directions. *IEEE Access*, *10*, 31306–31339.

Alnahhal, M., Antar, O., Sakhrieh, A., & Al Hazza, M. F. (2024). Analyzing energy consumption in universities: A literature review. *International Journal of Energy Economics and Policy*, *14*(3), 18–27.

Atef, E., Megahed, N., Elgheznawy, D., & Nashaat, B. (2024). Adaptive office buildings: Improving functional flexibility in response to shifting needs using kinetic technology. *Architectural Engineering and Design Management*, *20*(4), 946–971.

Benitez, G. B., Da Silveira, G. J., & Fogliatto, F. S. (2019). Layout planning in healthcare facilities: A systematic review. *HERD: Health Environments Research & Design Journal*, *12*(3), 31–44.

Carranza, C., Juárez, E., Carreto-Binaghi, L. E., Chávez-Domínguez, R. L., García-Ramos, M. A., Viettri, M., ... & Torres, M. (2025). Biological sample storage in biomedical research. *Clinica Chimica Acta*, 120538.

Cheng, H., Jia, S., Jiao, J., Chen, X., Deng, T., Xue, C., Dong, M., Zeng, J., Chen, C., Wu, H., He, M., & Han, B. (2024). Stabilization of Cu^{+} sites by amorphous Al_2O_3 to enhance electrochemical CO_2 reduction to C_2+ products. *Green Chemistry*, *26*(26), 2613–2622.

Gao, W., Wu, Z., Zuo, K., Xiang, Q., Zhang, L., Chen, X., ... & Liu, H. (2024). From biosafety to national security: The evolution and challenges of biosafety laboratories. *Laboratories*, *1*(3), 158–173.

Gao, W., Wu, Z., Zuo, K., Xiang, Q., Zhang, L., Chen, X., ... & Liu, H. (2025). Global safety and health: The history of high-level biosafety laboratories toward large scientific facilities. *Laboratories*, *2*(1), 3.

Gerarden, T. D., Newell, R. G., & Stavins, R. N. (2017). Assessing the energy-efficiency gap. *Journal of Economic Literature*, *55*(4), 1486–1525.

Gericke, K., Eckert, C., & Stacey, M. (2022). Elements of a design method – A basis for describing and evaluating design methods. *Design Science*, *8*, e29.

Hafez, F. S., Sa'di, B., Safa-Gamal, M., Taufiq-Yap, Y. H., Alrifaey, M., Seyedmahmoudian, M., ... & Mekhilef, S. (2023). Energy efficiency in sustainable

buildings: A systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research. *Energy Strategy Reviews, 45*, 101013.

Isah, M. B., Muhammad, Z., Lawan, M. M., Alkhamis, A. I., Goni, B. W., Oakley, S. S., ... & Maina, M. B. (2024). Setting up a state-of-the-art laboratory in resource limited settings: A case study of the biomedical science research and training centre in Northeast Nigeria. *European Journal of Neuroscience, 59*(7), 1681–1695.

Jovičić, S., & Milinković, N. (2025). Strategies for energy conservation and sustainability in medical laboratories. *Critical Reviews in Clinical Laboratory Sciences, 62*(8), 585–603.

Joshi, S., Prajapati, S. K., Sharma, V., Sharma, D., & Gupta, M. M. (2025). Wet-lab techniques for characterizing bioinspired materials and structures for regenerative medicine. In *Principles of bioinspired and biomimetic regenerative medicine* (pp. 819–859). Springer Nature Switzerland.

Kwong, Q. J., Abdullah, J., Tan, S. C., Thio, T. H. G., & Yeaw, W. S. (2019). A field study of indoor air quality and occupant perception in experimental laboratories and workshops. *Management of Environmental Quality: An International Journal, 30*(2), 467–482.

Leal Filho, W., Salvia, A. L., Do Paço, A., Anholon, R., Quelhas, O. L. G., Rampasso, I. S., ... & Brandli, L. L. (2019). A comparative study of approaches towards energy efficiency and renewable energy use at higher education institutions. *Journal of Cleaner Production, 237*, 117728.

Madhu, A., Cherian, I., & Gautam, A. K. (2022). Interdisciplinary approach to biomedical research: A panacea to efficient research output during the global pandemic. In *Coronavirus drug discovery* (pp. 331–347). Elsevier.

Meder, D., Morales, M., Pepperkok, R., Schlapbach, R., Tiran, A., & Van Minnebruggen, G. (2016). Institutional core facilities: Prerequisite for breakthroughs in the life sciences. *EMBO Reports, 17*(8), 1088–1093.

Meyn, S. M., Ramirez-Aguilar, K. A., Gregory, C. W., Mische, S., Ott, A. W., Sol-Church, K., ... & Taatjes, D. J. (2023). Addressing the environmental impact of science through a more rigorous, reproducible, and sustainable conduct of research. *Journal of Biomolecular Techniques, 33*(4).

Mostafavi, A. (2022). Architecture, biometrics, and virtual environments triangulation: A research review. *Architectural Science Review, 65*(6), 504–521.

Mu'azu, A. I. (2015).*Sustainable design strategy: Assessment of the impact of design variables on energy consumption of office buildings in Abuja, Nigeria* [Doctoral dissertation, University of Portsmouth].

Mukherjee, S., Malik, P., & Mukherjee, T. K. (2023). Establishment of a cell culture laboratory. In *Practical approach to mammalian cell and organ culture* (pp. 43–82). Springer Nature Singapore.

Ochedi, E. T., & Taki, A. (2019). Towards energy efficient buildings in Nigeria: Challenges and opportunities. *Journal of Engineering and Architecture, 7*(2), 125–133.

Okonta, D. E. (2023). Investigating the impact of building materials on energy efficiency and indoor cooling in Nigerian homes. *Heliyon, 9*(9).

Onuh, P., Ejiga, J. O., Abah, E. O., Onuh, J. O., Idogho, C., & Omale, J. (2024). Challenges and opportunities in Nigeria's renewable energy policy and legislation. *World Journal of Advanced Research and Reviews*, *23*(2), 2354–2372.

Saini, L., Meena, C. S., Raj, B. P., Agarwal, N., & Kumar, A. (2022). Net zero energy consumption building in India: An overview and initiative toward sustainable future. *International Journal of Green Energy, 19*(5), 544–561.

Saleh, N. U. M., Enaburekhan, J. S., Ali, K. I., Bala, A., Isah, M., & Muhammad, J. Y. U. (2023). Energy audit of Al-Qalam University, Katsina State Nigeria: A simulation approach. *World Academics Journal of Engineering Sciences*, *10*(2), 17–25.

Sayers, E. (2021). Laboratories. In *Metric handbook* (pp. 25-1). Routledge.

Sreepadmanabh, M., Sahu, A. K., & Chande, A. (2020). COVID-19: Advances in diagnostic tools, treatment strategies, and vaccine development. *Journal of Biosciences*, *45*(1), 148.

Umeh, C. A., Nwankwo, A. U., Oluka, P. O., Umeh, C. L., & Ogbonnaya, A. L. (2024). The role of renewable energies for sustainable energy governance and environmental policies for the mitigation of climate change in Nigeria. *European Journal of Applied Science, Engineering and Technology*, *2*(2), 71–98.

World Health Organization. (2020).*WHO guidance on implementing regulatory requirements for biosafety and biosecurity in biomedical laboratories: A stepwise approach.*

Zhang, A. X., Muller, M., & Wang, D. (2020). How do data science workers collaborate? Roles, workflows, and tools. *Proceedings of the ACM on Human-Computer Interaction*, *4*(CSCW1), 1–23.