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RESEARCH PAPER

Bio-cooling façade in tropical climate

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Abstract. The purpose of this paper is to explore how building design requires consideration of both energy consumption and environmental impacts of the construction and maintenance processes. The increasing energy consumption and construction waste are concerning trends within the building industry. In response to this issues, the concept of circular economy has gained prominence, emphasizing the need to restore, rebuild, and regenerate resources in a sustainable manner. This research focused on Bio-Cooling Façades (BCF) in tropical climates through the assessment of four parameters including the biomaterial, cooling façade, energy consumption, and building circularity. This was conducted through a comparative analysis of existing and eight proposed BCF configurations designed to reduce energy consumption and increase building circularity. The results show that applying BCF at a glazing size of 40% reduces solar heat radiation, lowers building energy consumption, and minimizes potential construction material waste in countries with tropical climates. These findings assist architects and the industry in defining the optimal building façades for cooling, ultimately reducing energy consumption.

Keywords: Bio-based material; cooling; façades; tropical climates

1. Introduction [First level heading]

The substantial expansion of the building industry is raising environmental concerns due to its rapid growth and significant impact (Ahram & Zakaria, 2023). Over the past 28 years, global energy demand has increased by 4,559 tons (Kapilan et al., 2023). The built environment is a significant contributor to global energy consumption and carbon emissions. The building sector the highest consumer of energy, especially in tropical climates, where nearly all structures rely on HVAC systems, resulting in elevated energy consumption (Bougdah & Sharples, 2009; Lechner, 2015). Energy consumption in buildings typically account for around 39% (and up to 50%) of total energy consumption (Bougdah & Sharples, 2009; Knotts et al., 2011). Moreover, the high energy consumption in educational spaces has become an issue of concern in recent years (Khani et al., 2022). In tropical and subtropical regions, cooling in building is important for thermal comfort, especially in public buildings (Boukhanouf et al., 2015). This is mainly because people currently spend 87-90% of their time, or about 20 hours per day, indoors (Jara-Baeza et al., 2023; Klepeis et al., 2001). Several factors affect energy use in buildings, including climate, building envelope, energy systems, building operation and maintenance, occupant behavior, and activities.

The growing emphasis on sustainable development within the construction industry is stem from its contribution to approximately 40% of global energy consumption and about one-third of

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greenhouse gas (GHG) emissions in the built environment (Nielsen et al., 2016). This has led to the implementation of various programs worldwide to achieve the Sustainable Development Goals (SDGs) while considering environmental impacts. It is important to note that the building sector plays a crucial role in achieving SDG 7 and 12, which focus on energy use, as well as SDG 13, which address climate change. Sustainable and modern energy consumption are key goals of the 2030 global agenda (Maurer et al., 2020). The ensure effective implementation, these goals need to be associated with specific projects, as outlined in the 2030 Agenda. This is necessary because stakeholders in the building industry often operate within a linear economy, which focuses on the disposal of remnant of raw materials used.

The linear economy has been reported to significantly influence increased energy use and emissions production due to the high consumption of raw materials (Nayak, 2022). This shows that the linear economy is not appropriate in the current era, given the focus on climate change and environmental issues. Therefore, there is a need to shift to a circular economy (CE), which emphasizes using materials and products more efficiently and developing resources within a closed-loop system (Brunklaus & Riise, 2018; van der Zwaag et al., 2023). The CE concept, primarily championed by the European Union and China, has garnered increased attention since the establishment of the Ellen MacArthur Foundation (EMF) in 2010. This is mostly associated with the utilization of organic waste streams, the cascade use of bio-based goods and associated wastes, as well as reuse, remanufacture, and recycle processes (Carus & Dammer, 2018). It focuses on using basic building materials and decorative objects in their original forms, reprocessed materials, and those generated wholly or partly from renewable biological origins, or by-products and biowastes of plants and animals (Le et al., 2023). The application of CE principles could significantly mitigate these risks.

The design of buildings in line with the principle of the CE also requires careful consideration of energy consumption and material circularity. This research aims to investigate existing façades in buildings located in tropical climates to recommend design alternatives using Bio-Cooling Façade (BCF). This goal is to reduce energy consumption and enhance building circularity. The results are expected to benefit stakeholders in the building materials industry as well as designers by promoting building design and construction practices that align with the SDGs.

The broad scope and variety of energy conservation strategies include the application of Façade System Elements. One of the design strategies commonly used in this system is BCF, which was analyzed in this research based on four parameters: including biomaterials, cooling façades, energy consumption, and building circularity. This analysis was necessary because previous research focused solely on reducing building energy consumption without considering the overall environmental impact. For example, the use of bio-based materials in façade cooling interventions has minimal environmental impact compared to technical alternatives, as demonstrated by the building circularity assessment. Moreover, BCFs were applied to minimize energy consumption while enhancing building circularity to support architectural sustainability.

2. Literature review

The solution to the problems identified in the introduction is the application of BCF. This section discusses low energy consumption and circularity in building façades as a basis for planning suitable BCF solutions for tropical climates. The discussion begins with an explanation of the concept associated with building energy performance to achieve low energy consumption, followed by an overview of building circularity in the façades.

2.1. Building energy performance to achieve low energy consumption

Building performance is usually influenced by the design and materials used, which in turn influence energy efficiency, thermal comfort, and occupant productivity (Xie et al., 2023). Moreover, user behavior or activities significantly impact energy efficiency, particularly through the use of heating and cooling systems in different climatic conditions (Hernandez-Cruz et al., 2023). This subsequently has a substantial effect on overall energy performance of a building. Therefore, there is a need for well-designed systems that can minimize negative impacts on the natural and built environment to increase sustainability (Al-Shargabi et al., 2022).

The design characteristics and model of a building envelope can negatively impacts on energy consumption (Al-Shargabi et al., 2022). This means that the performance of a building, particularly in terms of the thermal insulation and envelope, is a key factor in determining its energy efficiency (Xu et al., 2023). Some studies have discussed the importance of building façades for achieving low energy consumption in tropical climates, specifically focusing on cooling aspects. Factors such as the size of glass windows, insulation, thickness, and materials used for the wall, as regulated by ISO standards, have been emphasized (Denis, 2016). Another study compared the fenestration system area, consisting of glass and sills, with the gross area based on guidelines stated in Standar Nasional Indonesia/Indonesian National Standards (SNI) 6389:2020 (National Standardization Agency, 2020). The results showed that the Window-to-Wall Ratio (WWR) for single-skin façade ranged between 25% and 50% (DKI Jakarta Provincial Government, 2012), while the optimum solution was found to be the combination of 30% WWR with a wall reflectance of 0.8 (Mangkuto et al., 2016). However, another research proposed 40% WWR for north-facing orientations in Depok, Indonesia (Dewi et al., 2022). These findings indicate that the selecting appropriate materials for façade requires considering transmission values, radiation, and other factors influencing room temperature. Much attention also needs to be paid when designing glass buildings, given the ability of glass materials to transmit light and solar energy, which effects the indoor performance of a building (Lori et al., 2019).

2.2. Bio-cooling façade (BCF) in tropical climate

A cooling system façade is a building feature typically used to reduce maximum indoor surface temperatures and improve minimum indoor surface temperatures by up to 7°C (Manso & Castro-Gomes, 2016). A previous study showed that wall and thermal insulation could lower indoor temperatures by approximately 1-5°C (Mirrahimi et al., 2016). This shows that it is possible to significantly reduce energy consumption and increase thermal comfort using better-insulated outer wall materials and windows (Sevilgen & Kilic, 2011). It has also been stated that heat transfer occurs at a lower rate across materials of low thermal conductivity compared to those with high thermal conductivity (Huang et al., 2017). Thermal conductivity is defined as the property of a material to conduct heat.

Façades made from bio-based materials can support the CE due to their potential as a promising resource for sustainability in the present century (Pujadas-Gispert et al., 2020). Another important point is that façades significantly contribute to thermal comfort (Sarihi et al., 2021). As previously discussed, cooling effects and bio-based materials are crucial for the longevity of a building, as they often have a longer lifespan compared to other components. Therefore, these materials are necessary in façade design to reduce energy consumption and enhance circularity in buildings.

Certain benchmarks for cooling façades incorporate moisture-absorbing insulation and outer walls designed to retain moisture while shielding the insulation from direct sunlight. This is necessary because moist insulation tends to degrade rapidly when directly exposed to sunlight. Therefore, bio-based materials such as BCF are introduced as a solution for cooling indoor spaces in buildings, due to the easy recyclability and low thermal conductivity (Binici et al., 2016). The application of these materials has evolved over the years (The Manufacturer, 2015) because of their sustainability in terms of performance, energy usage, availability in a given context, and the quality of the space provided (Hassan, 2020).

Moist insulation is not expected to contain any liquid due to its role in converting solar heat into the building and withstanding moisture, as liquid is more suitable for passive heating. Moist insulation is typically used for trapping humidity (for cooling). However, there is a challenge with using moist insulation because it may not insulate effectively in direct sunlight. Additionally, the materials commonly used for this type of insulation should not be exposed directly to sunlight, especially in tropical climates like Indonesia, to avoid deterioration. For this reason, an outer wall

Table 1. Material intervention for moist insulation and outer wall

Functions	Material	Lifespan	Recyclability	Fire resistance	Challenges	Thermal conductivity (W/m.K.)	Density (kg/m^3)
Moist Insulation	Mycelium	15-20 years (Osman & Amanor-Boadu, 2023)	Can be recycled through mechanical and biological processes (McGaw et al., 2022)	Excellent (Marcus Fairs, 2021)	Biodegradation and need water absorption (Zhang et al., 2022)	0.03-0.06 W/m.K. (MaterialDistrict, 2022)	230-557 (Tacer-Caba et al., 2020)
	Cellulose	15-30 years (Foroughi et al., 2021; John, 2022)	Can be recycled through mechanical and biological processes (Yu et al., 2020)	Good (Mohamed & Hassabo, 2015)	Needs to be protected from moisture and heat radiation (John, 2022)	0.035-0.04 W/m.K. (Ayadi et al., 2023)	1480-1500 (Ganesan et al., 2019)
	Natural Fiber	25-100 years (Li et al., 2020; Rana et al., 2014)	Can be recycled through mechanical and biological processes (Seydibeyoğlu et al., 2017)	Good (Pornwannachai et al., 2018)	Moisture absorption, fungal growth, UV degradation (Dhir et al., 2020)	0.03-0.06 W/m.K. (Stapulionienė et al., 2016)	1400-1500 (Ganesan et al., 2019)
	Rockwool	50 years (Rockwool.com, 2023)	Recyclable and can be transformed into new rockwool products (Asdrubali et al., 2015)	No reaction/incombustible (A1-A2) (Asdrubali et al., 2015)	Adding or replacing insulation in some parts, it can be challenging to replace in others (such as cavity walls or below ground), important to use a durable insulation product that will perform consistently throughout the building's lifetime (Rockwool.com, 2023)	0.033-0.04 W/m.K. (Asdrubali et al., 2015)	120 (Uris et al., 1999)
Outer Wall	Bamboo Petung/ Betung	4-10 years (Hornaday, 2020; Petruzzello, 2024)	Chemical, biological, and physical recycling (Manandhar et al., 2019)	A flammable material that can be affected by heat and fire (Solarte et al., 2021)	Need coating to increase fire resistance (Solarte et al., 2021)	0.55-0.59 W/m.K. (Shah et al., 2016)	650-800 (Yang et al., 2021)
	Stone Cladding Gravel Gray	12-70 years (Ferreira et al., 2021)	Can be recycled and reused (Klemm & Wiggins, 2016)	Fire resistant material (BRE Global Ltd, 2020)	Degradation (Pires et al., 2022)	0.36 W/m.K. (Abu Dabous et al., 2022)	1840 (Abu Dabous et al., 2022)

with a textured surface is preferable to maintain thermal insulation and control moisture. The texture of the outer wall can also help capture and transfer rainwater as moisture into the insulation system. Moreover, bio-based materials are ideal for this purpose due to their low thermal conductivity.

These materials are usually selected based on the availability in Jakarta, relevance to the hot and humid climate, long lifespan, recyclability, good fire resistance, and low thermal conductivity, as presented in Tables 1. Some of these materials include mycelium (fungus), cellulose (bacteria), natural fiber from plant fibers, and rockwool. The most relevant options for the outer wall are bamboo pentung or betung and stone cladding in the form of gravel, which are typically selected for their ability to respond well to temperature and humidity, as well as suitability for use as structural walls in buildings. These selections led to the development of the following eight interventions: Bamboo and Mycelium (BM), Bamboo and Cellulose (BC), Bamboo and Natural Fiber (BNF), Bamboo and Rockwool (BR), Gravel and Mycelium (GM), Gravel and Cellulose (GC), Gravel and Natural Fiber (GNF), dan Gravel and Rockwool (GR).

BCF produced using bio-based materials are expected to have optimal circularity performance and significantly reduce energy consumption. The selection and application of these bio-based materials depend on the suitability for tropical climates. Previous studies on cooling façades have predominantly focused on indoor thermal comfort and its influence on energy usage in buildings. However, few studies discuss the circularity of the façade materials, despite their substantial impact on energy usage from the initial phase of construction to end of materials' lifecylce. Therefore, this research was conducted with consideration for these two factors, aiming to maximize efforts to support the actualization of SDGs (7, 12, and 13) and to reduce the environmental impact of construction processes.

3. Research method

3.1. Proposed concept

The main focus of this research is to determine the design strategies for façades using BCF interventions. BCFs have six parameters (orientation, external wall, external roof, glazing size or WWR, external shading, and glazing type), but only the external wall and WWR were selected due to the relevance to the identified problems. This selection was made because the case study's WWR was observed to be large, and the external wall had experienced some damage. Additionally, the space was found to be cool, and the façade was bio-based, which were considered beneficial for thermal insulation. Therefore, the intervention was introduced to reduce energy consumption. This is crucial, as buildings contribute 30-40% of total energy consumption globally, directly affecting the users. Furthermore, BCFs can improve thermal comfort and increase the productivity of building users by 9.2%. The BCF was developed based on existing designs adopted from comparative studies. This was achieved by simulating energy consumption and proposing the application of BCF using Rhino Grasshopper and the Material Circularity Indicator (MCI) Framework from Hoskins. The purpose was to produce BCF capable of reducing energy consumption and supporting circularity in buildings located in tropical climate.

The first step was to conduct a comprehensive literature review on the application of BCF as an energy conservation strategy in buildings to serve as a reference for the proposed intervention, as presented in Figure 1. The review was also focused on determining the parameters of energy consumption and building circularity parameters to be used for field measurement, input into the simulation conducted using Rhino Grasshopper, and calculations through the MCI Framework. The expected outputs were energy consumption in kWh and building circularity value in percentage, with due consideration for the biomaterial used and the glazing size (40%). Data were collected from the project documents, such as working drawing and AutoCAD files of the case study as well as on-site surveys to determine the actual conditions and fill in any gaps not covered in the working drawings. The purpose of this first step was to define the existing geometry and material properties needed for the simulation and calculation.

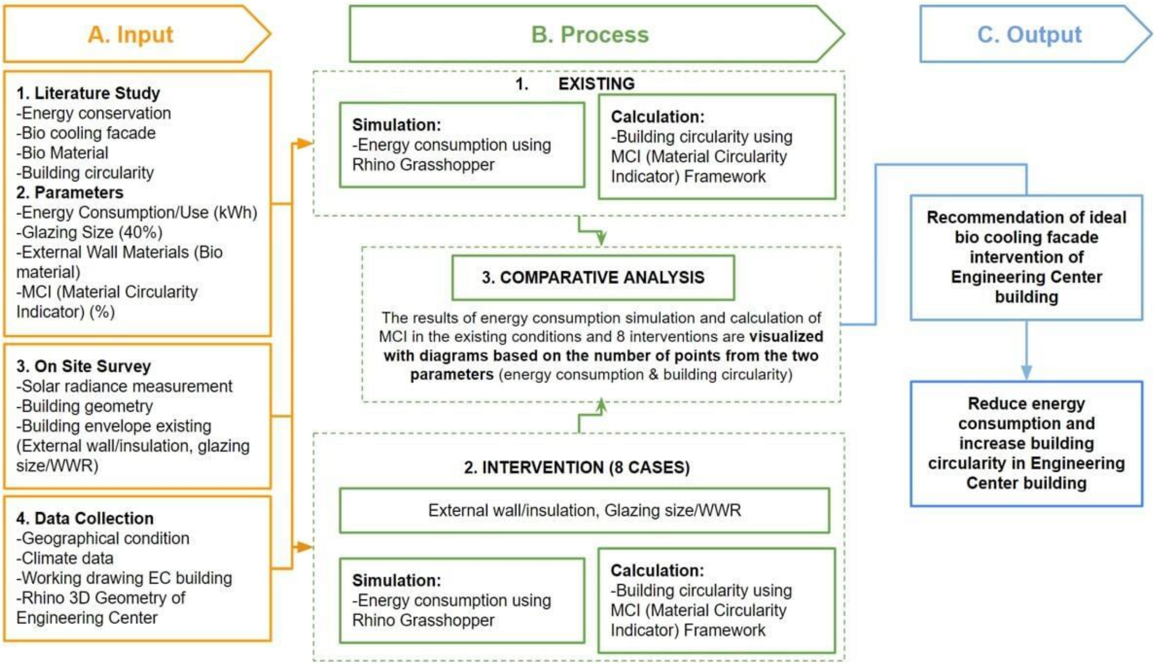


Figure 1. Research method flow

The next step was to apply the building geometry and materials obtained from the previous step to perform simulations using Rhino Grasshopper and conduct other calculations in an Excel spreadsheet. The purpose was to identify potential BCF solutions to recommend for buildings in tropical climates. This was achieved by first simulating the energy consumption and calculating the building circularity for the existing condition, followed by applying eight interventions as external or insulation walls with different glazing sizes and WWR. The results obtained from the two processes were then compared to holistically determine the ideal parameters for BCF.

3.2. Honeybee energy consumption simulation

The main software used in this study are Rhinoceros and Grasshopper. Rhinoceros is a software used for 3D modeling, similar to Autodesk 3Ds Max and Revit. It was developed by Robert McNeel and Associates. Grasshopper is a visual programming software used to create programs for models in Rhinoceros. These two software programs can perform various types of simulations related to building performance, assisted by several plug-ins (food4rhino). This simulation also uses Honeybee plug-ins to input weather data and energy consumption from cooling load simulations. The purposes of the simulation is to create the Engineering Center (EC) building geometry in Rhinoceros based on the EC working drawings, which are imported into the Rhinoceros model as a 2D model which is then traced into a 3D shape.

The energy consumption in the existing design of the case study was simulated with fixed settings to determine the output in the form of monthly cooling loads using the processes presented in Figure 2. The simulation script was later modified based on the interventions, including the changes in the characteristics of the insulation materials and outer walls, such as thickness, conductivity, and density.

3.3. Calculation of material circularity indicator (MCI)

The building circularity was calculated using a CE consulting framework called the MCI from Hoskins. This was based on a table containing various inputs, including component names, material lifespan in years, material weight in kilograms (kg), quantity of material used, input materials (material type, source, and whether regenerative), and output materials (collection rate and destination), as the input in Figure 3. The type of material for each component can include options such as aluminium, bioplastics, composites, electronics, glass, natural materials, plastics, and steel. This research specifies the materials in natural materials because it uses bio-based materials.

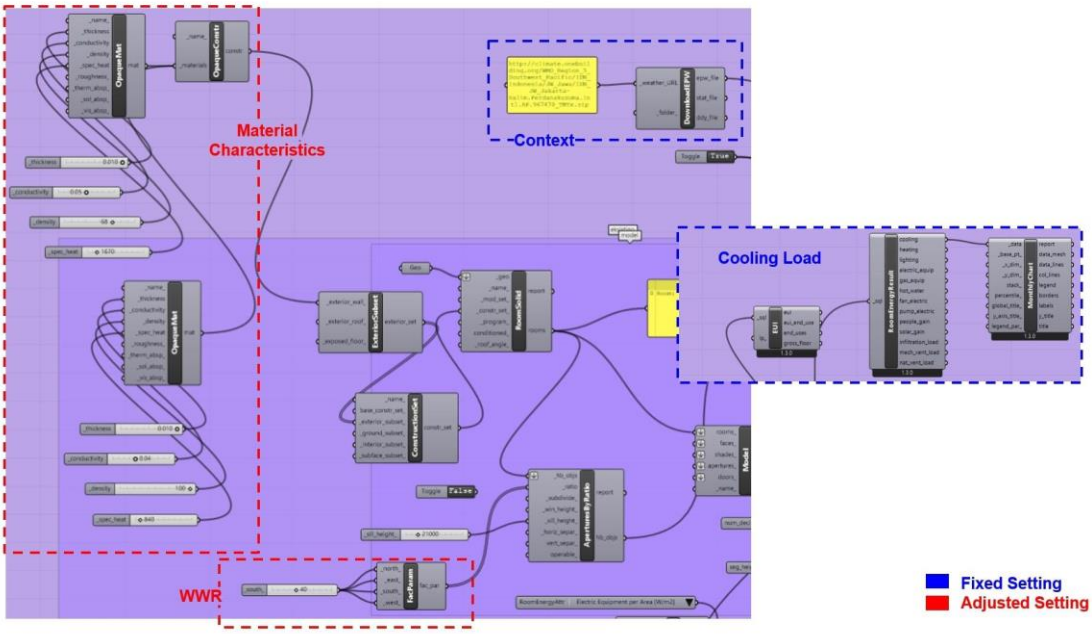
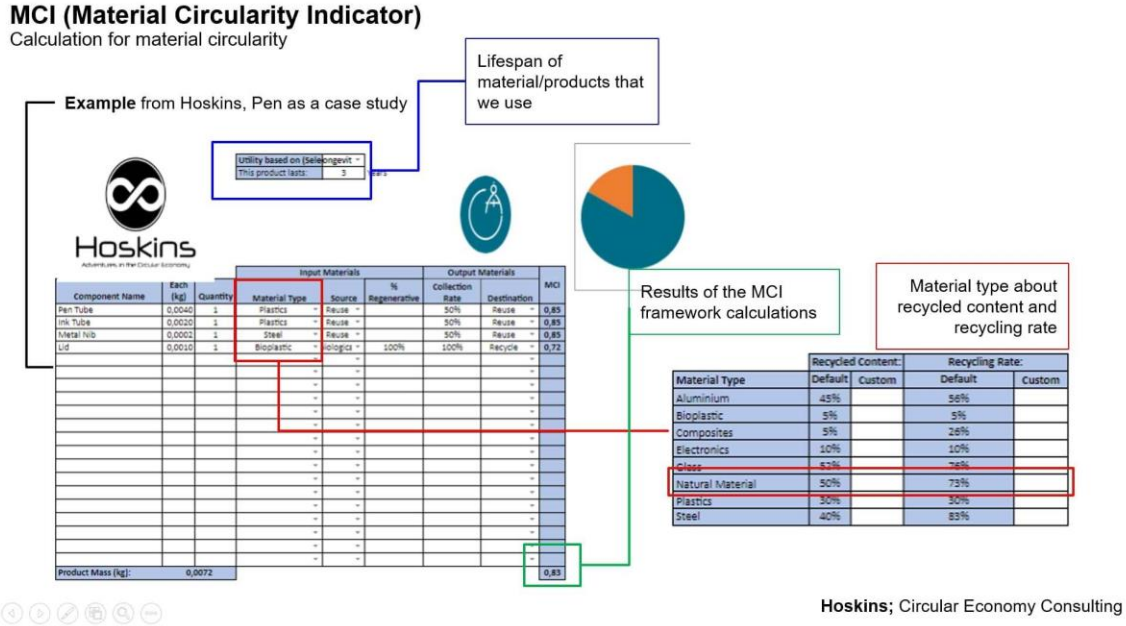


Figure 2. Energy consumption script using honeybee in grasshopper



MCI (Material Circularity Indicator)
Calculation for material circularity

Example from Hoskins, Pen as a case study

Lifespan of material/products that we use

Utility based on (Sele	ongevit
This product lasts:	3

			Input Materials			Output Materials		
Component Name	Each (kg)	Quantity	Material Type	Source	% Regenerative	Collection Rate	Destination	MCI
Pen Tube	0,0040	1	Plastics	Reuse		50%	Reuse	0,85
Ink Tube	0,0020	1	Plastics	Reuse		50%	Reuse	0,85
Metal Nib	0,0002	1	Steel	Reuse		50%	Reuse	0,85
Lid	0,0010	1	Bioplastic	iologics	100%	100%	Recycle	0,72
Product Mass (kg):	0,0072							0,83

Results of the MCI framework calculations

Material type about recycled content and recycling rate

	Recycled Content:		Recycling Rate:	
Material Type	Default	Custom	Default	Custom
Aluminium	45%		56%	
Bioplastic	5%		5%	
Composites	5%		26%	
Electronics	10%		10%	
Glass	52%		76%	
Natural Material	50%		73%	
Plastics	30%		30%	
Steel	40%		83%	

Hoskins; Circular Economy Consulting

Figure 3. MCI framework from Hoskins

The material type allows the calculator to select suitable recycled content for your component. Default values are specified, but they should be used with caution as they may be product or region specific. Using the table at the bottom of the calculator, you can change the provided figures. The use of cardboard, a natural material with typically the highest recycling rate, can be an example where this might make sense. The amount of each component captured by the user is also taken into account. Circularity cannot be assumed for materials that are not accounted for, and as a consequence, products that were not returned are regarded as no longer part of the circular system. The destination has been specified for each component, with possibilities including reuse, manufacturing, recycling, composting, energy recovery, and landfilling. Naturally, composting applies only to biological materials. Under specific conditions laid out in the methodology, energy recovery can only be considered a circular option for regenerative biological materials. The results were obtained in percentages after processing and visualized through a pie chart.

4. Case study

4.1. Engineering Center Faculty of Engineering of Universitas Indonesia

The Engineering Center (EC) is an educational building in the Faculty of Engineering of Universitas Indonesia (FTUI), located in Depok City, West Java, Indonesia. The building was chosen as case study to evaluate the existing strategies used in designing the façade system and to propose alternative designs using the BCF concept. The selection of this building was based on its location in a humid, tropical climate at a latitude of 6°21'44.63 south and longitude of 106° 49' 30.51 east.

The climatic conditions of Depok city were assessed over a year, with temperatures recorded in the range of 23°C - 33°C and an average of 26.5°C. The city was also reported to have a hot and humid climate for 29-31 days every month, with intense humidity recorded as the average for nearly a full month (30 days). Additional data considered include rainfall and daylight conditions due to their influence on the materials to be used.

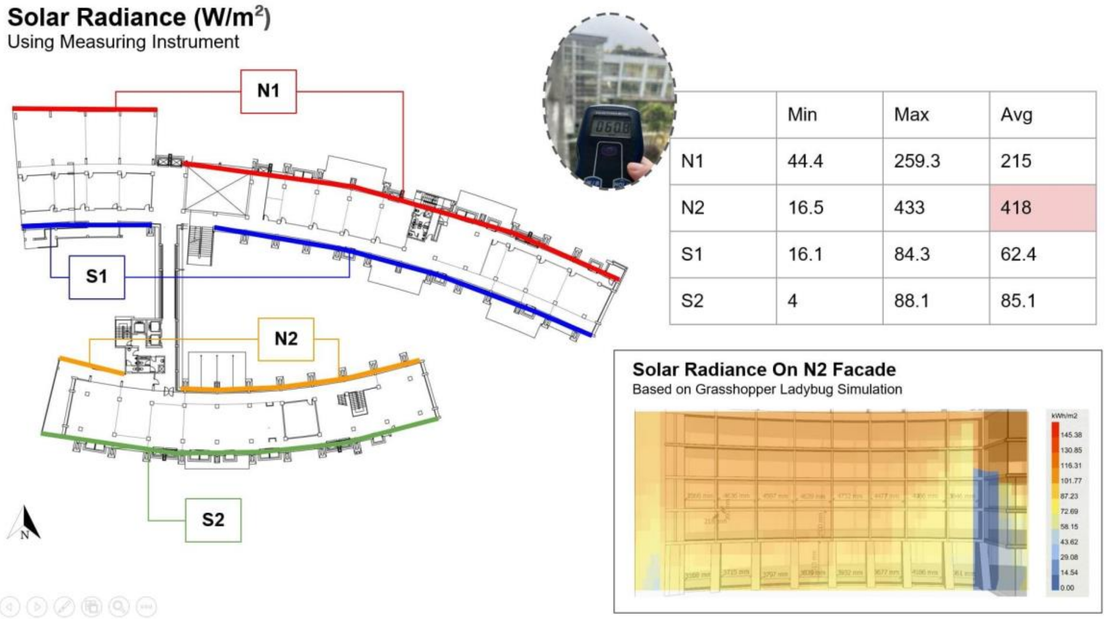
EC of FTUI was observed to have various spaces, such as student learning centers, offices, and shops. The function of these spaces needed to be considered due to their differing requirements. The building also had a façade with almost 100% WWR in each room and over 50% WWR in the north-facing side, resulting in high solar heat radiation. Moreover, central air conditioning (central AC) was used continuously from morning to night (09.00 - 19.00 WIB) in different rooms, leading to high energy consumption because most of the rooms were frequently vacant. This high energy consumption is common in tropical climate countries, such as in Indonesia, where AC is one of the major energy consumers. Therefore, it is necessary to design buildings with considerations for reduction energy consumption. This has led to the application of several technical materials, such as rusty aluminum or iron frames as façade. However, these materials have the potential to become construction wastes.

The solar radiance was measured on-site using a solar power meter, and the results are presented in Figure 4. The four sides of the building, including two north and two south sides, were measured. The results showed that the north sides received greater heat radiation from the sun, with the N_2 side having the highest radiation compared to the south sides. In addition to the one-site survey, solar radiance was also assessed using a Grasshopper Ladybug simulation. The results from the simulation were similar to the on-site measurements and were further used as the basis for planning BCF design interventions.

5. Result and discussion

5.1. Form and details of BCF

Previous research stated that a building or room in the Depok city, Indonesia, with a WWR of 40% on the north side has a good fenestration system to ensure appropriate cooling and energy savings. Therefore, the façades were designed based on the consideration that the glazing size and openings were at the eye level to support the work and activities of the building’s users. This led to the adoption of a 40% glazing size for the design, as presented in Figure 5.



	Min	Max	Avg
N1	44.4	259.3	215
N2	16.5	433	418
S1	16.1	84.3	62.4
S2	4	88.1	85.1

Figure 4. Solar measurement

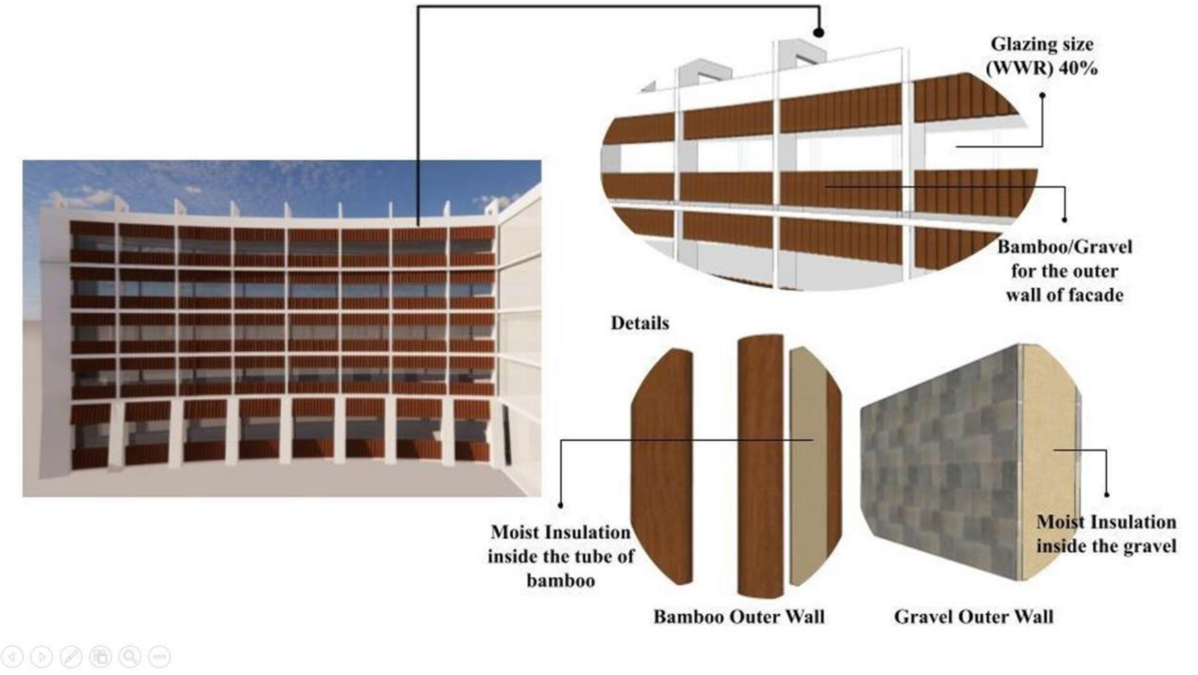


Figure 5. Front view of the bamboo façade

The outer walls of the façade were observed to have a natural material texture without any extra processing. The purpose of the application was to maintain the lifespan of the façade, considering the area's humidity, temperature, changing weather, and direct sunlight. The outer walls were also designed to support the cooling process in the building and reduce energy consumption by sustaining indoor thermal comfort. Furthermore, bio-based materials were selected for the outer wall due to their low thermal conductivity and support for CE in buildings.

Before the intervention, the height of the glass in the EC of FTUI, extended from the floor to ceiling. During the intervention, a WWR of 40% was maintained for the façade by replacing the remaining portion with bamboo or gravel cladding, as presented in Figure 6. The bamboo wall used bamboo frames because the circular shape of its profiles was not compatible with aluminum frames. However, the gravel wall maintained the aluminum frames due to the ease of installation.

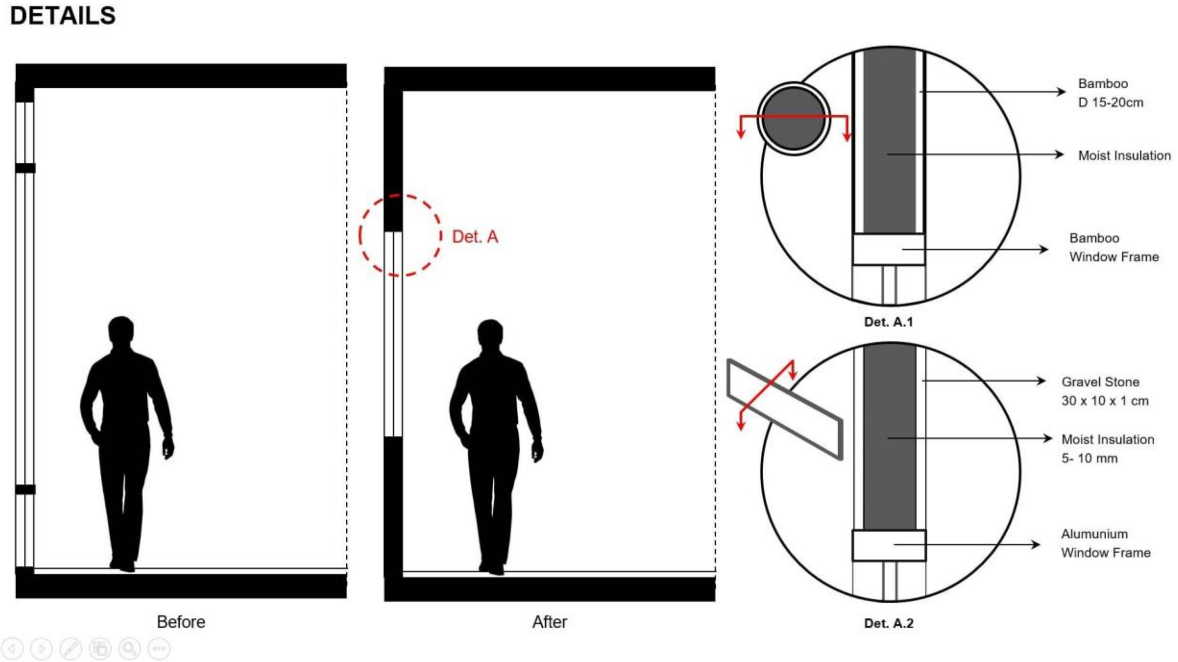


Figure 6. Detailed description of the existing façade and BCF intervention

5.2. Comparative analysis of the cooling energy load simulated

The simulation results presented in Figure 7 showed that insulation was more important for reducing energy consumption than the outer wall. This was because adding thermal insulation to the building reduced to the cooling energy load by 20- 29% (Mirrahimi et al., 2010). The least energy reduction was observed in the combination of bamboo with mycelium and gravel with mycelium, while the largest reduction was seen with gravel and cellulose, as well as bamboo and cellulose. This indicates that cellulose insulation achieved the highest energy reduction, approximately 40%, regardless of the outer material used.

The simulation of the existing design showed that a very high amount of energy, in the range of 500-700 kWh, was consumed throughout the year. This was significantly higher compared to the alternative designs proposed using bio-based materials with a glazing size of 40%. Figure 7 shows that the smallest and largest reductions in energy consumption for the alternatives designed with outer walls and moist insulation were similar, as indicated by the kWh. This led to the conclusion that both bamboo and gravel stone cladding outer walls could be used environmentally friendly façade materials in areas with tropical climates.

5.3. Comparative analysis of MCI

The results presented in Figure 8 showed that the adoption of rockwool as moist insulation produced high building circularity values. It was also discovered that the outer wall influenced this value, as the application of bamboo as an outer wall and rockwool as a moist insulation produced the highest building circularity value of 63.7% compared to other design interventions. Comparison of this value to the existing conditions showed an increase of 53.7% in building circularity.

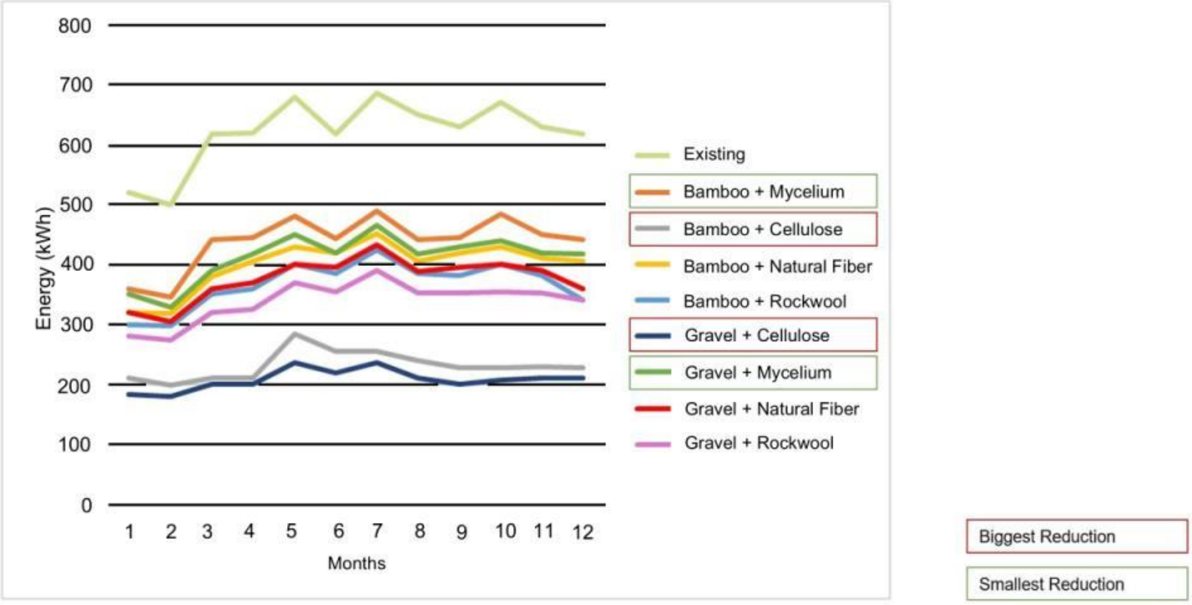


Figure 7. Comparative simulation of cooling energy load consumption

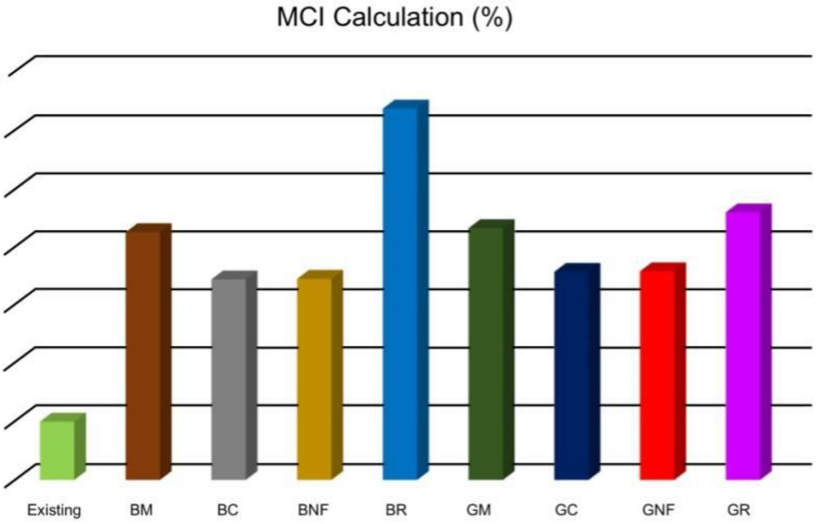


Figure 8. Comparative calculation of MCI

Figure 8 shows that the technical-based materials used in the existing design led to a low circularity of less than 10% in the building façade area. Moreover, it was generally observed that the application of other moist insulation materials, such as mycelium, cellulose, and natural fiber, did not produce significantly different results with the variations of outer walls used. This led to the conclusion that the rockwool moist insulation had the most significant influence on the circularity of the façade based on MCI calculations by Hoskins.

5.4. Ranking of potential BCF solutions

The points calculated from the two parameters, simulated energy consumption and building circularity values, were used to determine the ideal design to be applied to tropical climate areas. It was recommended that the EC FTUI should use rockwool as moist insulation, while either bamboo or gravel stone cladding could be used as the outer wall, based on the results presented in Figure 9. This was the ideal BCF intervention suggested for the case study based on the points calculated and presented in the following figure.

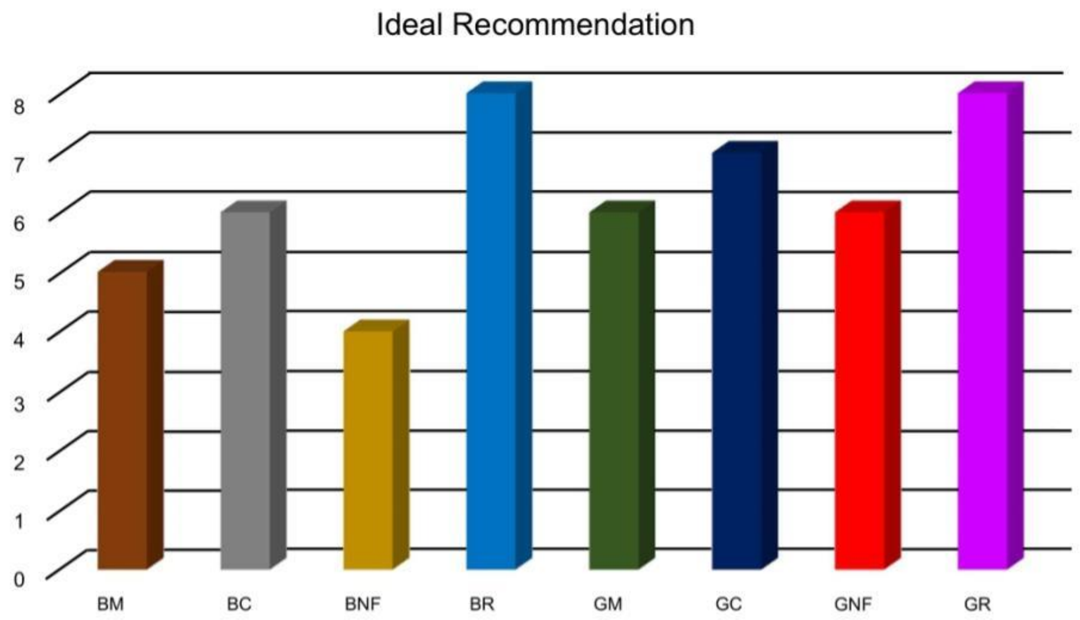


Figure 9. Ranking for the potential BCF intervention

The BR and GR were recommended as alternatives because they recorded highest ranking when compared to other designs. However, the two designs offer different advantages, with the BR having a higher assessment score for the MCI, while the GR demonstrated a greater reduction in energy consumption. These alternatives have great potential, but their direct application in buildings require careful consideration of some important aspects.

6. Conclusion and recommendation

In conclusion, this research investigated the existing façade design in the EC FTUI and recommended alternative BCF designs to reduce energy consumption and support building circularity. The simulations and calculations conducted led to the following results. First, the most effective strategy to reduce energy consumption is the application of gravel stone cladding and cellulose materials, while the least effective was bamboo and mycelium. Second, the reduction of the WWR to 40% had a significant impact on the reducing energy consumption. Third, the simulation of bamboo and gravel stone cladding as outer walls and cellulose as moist insulation had the greatest impact, reducing energy consumption by 40%. The MCI calculation also showed that the combination of bamboo and rockwool increased the MCI percentage by 53,7% compared to the existing condition. Fourth, the ranking based on energy consumption and MCI values showed that the ideal BCF design was the application of bamboo and gravel stone cladding as outer walls and rockwool as moist insulation. Meanwhile, the worst design was the adoption of natural fiber as moist insulation.

These results show that bio-materials can contribute to achieving building circularity and reducing energy consumption due to their high recyclability and thermal insulation properties. However, the application of these materials requires consideration of the climatic conditions of the building site. This is demonstrated by the fact that the application of the BCF design and the reduction of WWR to 40% address issues of high solar heat radiation, high energy consumption, and potential for increased construction material waste in the buildings located in tropical climates.

Future research should incorporate simulations or experiments to comprehensively address the implementation of sustainable architectural design for building façades. These endeavors are essential to validate the potential impact of high energy consumption influenced by solar heat gain on both energy efficiency and thermal comfort within buildings. In terms of energy conservation, the focus should extend beyond reducing energy consumption to also considering the convenience, as explored in this research. Moreover, the application of the recommended design alternatives requires further investigation regarding energy consumption and building circularity, as their efficacy cannot be assessed based on a single factor.

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