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A study on the effectiveness of biological growth resistant coatings on external building façade systems in the tropics

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ABSTRACT

Traditional façade cleaning processes can be dangerous, labour-intensive, and impairs the ease of façade maintenance. Thus, in improving the maintainability of the façade systems, facility managers search for novel strategies to reduce the cleaning cycles. Façade systems in tropical cities are frequently and severely affected by biological attacks such as algae. However, there is a considerable dearth of knowledge on the effectiveness of novel façade coating systems; proposed to prevent biological growth in tropical buildings. As part of an ongoing effort to create a material manual, the effectiveness of six commercially available façade coating products on three different substrates (granite, aluminium, rendering materials), of a building under Singapore's tropical conditions to inhibit biological growth is evaluated.

On-site photogrammetric data were collected over six months to analyse using an updated novel digital image processing procedure to evaluate the development of biological growth on the façade. A lifecycle cost (LCC) analysis is carried out for each type of façade coating application. The analysis from site measurements showed that all products exhibited improved performance on keeping the surfaces cleaner than the untreated façade surfaces. As the level of improvement varied between different substrates, a façade cleaning index is defined for each coating system. A lifecycle cost analysis showed varying results on the improvement in the performance of the products applied. A general reduction in cleaning cycles favours the facility's operating costs for granite and aluminium substrates. For rendering materials, the high cost associated with the application appeared to make the LCC less attractive.

1. Introduction

Building façade cleaning exercises are expensive operations due to its labour and machinery intensive nature and related safety concerns, and high resource requirements [1]. This is especially true for tropical cities such as Singapore where façade systems face multitudinous stress conditions under its tropical conditions; heightening the exposure for surface defects [2–4]. A common such surface defect can be identified as façade staining by atmospheric effects; generally due to staining by non-biological agents and staining by biological agents propagated by wind or rainwater [5]. Biological staining agents affect building façades that are close to vegetation. Under tropical conditions, these may refer to plant groups such as algae, fungi, mosses, ferns, and figs [6]. The appearance of biological growth is abundant in tropical regions and is considered a common surface defect found on buildings.

Left unchecked, biological growth on façade surfaces will create an aesthetically subjective discolouration of various colours and different shades of green, orange, black or blue. Looking past the unpleasant aesthetics, biological growth can contribute to further weathering and premature deterioration of façade systems [6]. Various solutions are proposed for existing and new buildings as preventive measures that may minimize the occurrence of such defects. Such biological growth resistant coatings can include biocidal films, self-cleaning superhydrophobic and photocatalytic coatings.

Facility managers better equipped with a good understanding of how biological growth propagate and how these biological growth resistant coatings can be used to inhibit it can make better decisions incorporating such solutions. This knowledge can help the facility managers prepare buildings against biological growth infestations; instead of merely conducting corrective measures. Therefore, determining and understanding the effectiveness of biological growth resistant coating

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system performance in real life applications can lead to improved maintainability of buildings and can help achieve realistic budgeting expectations from such novel coating systems [7]. Therefore, the objective of the current study is to study the effectiveness of commercially available façade coating systems to inhibit biological growth on granite, aluminium and rendering materials under tropical conditions.

1.1. Modes of biological growth removal from building façade

The current study considers the effectiveness of surface products against a wide range of biological growths (e.g. *Chlorococcum, Trentepohlia odorata, cyanobacteria, etc.*). Biological growth on façade is characterised by two broad attributing factors, i.e. factors attributed to the environment and factors attributed to the building envelope [8]. The environmental factors consist of the climate, thermal amplitude, precipitation, hygrometry (humidity), distance from the sea and presence/absence of vegetation. Precipitation and hygrometry directly affect the availability of water on to building facades, which is widely known as one of the key requirements for biological growth. In Singapore, the high humidity and precipitation result in buildings experiencing high amounts of water contact throughout the year. The closeness of the building to the sea can also result in higher atmospheric humidity, leading to a greater chance of biological growth. Building related factors affecting biological growth are excess surface moisture, windborne transport (orientation), and rain streaks that carry the algae spores down a façade [5,9]. Moreover, façade surface chemical characteristics dictate how the biological growth propagates, depending on the considered biological organism. According to Ref. [10] the optimal pH range favouring biological growth can fall between 5 and 7, as well as, between 2 and 11. Certain biological growth can occur at even higher values ($pH > 11$). In practice, carbonation caused by the use of high alkaline fresh concrete during construction lowers surface pH. This results in creating a favourable environment for biological growth on finished concrete surfaces [11]. On the other hand, mould and fungus growth can be expected on façade material such as concrete which possess pH values of over 12, due to cultures transported from surface dust deposits [12].

A majority of biological growth on buildings are attributed to improper designs which result in water retention on the façade surface, hence, the objective of many observed preventive measures against biological growth is to improve the building design to provide proper drainage and to ensure high-quality workmanship [13]. Prevention of façade water condensation is a viable solution for new buildings. However, existing buildings may find it difficult to engage in major design overhauls or renovation works. Remedial actions for biological growth include using high-pressure water jetting and manual scrubbing, biocidal wash, biological growth-resistant paint, and applying affected walls with anti-condensation coatings. However, all these actions carry certain limitations. Moreover, there is a considerable lack of knowledge on the efficacy of more recent and innovative solutions in preventing microbial growth on building façades under tropical conditions.

Abrasive cleaning is heavily reliant on manpower, increasing the cost of facility maintenance. Furthermore, it can disrupt normal building operations, can damage façade surfaces, and does not prevent the biological growth from forming again. Chemical biocides can be washed off the surface and are found to be photodegradable, hence, cannot be considered a long-term solution [14,15]. The runoff from these biocides can sometimes be harmful to the environment [16]. Biological growth resistant paint can restrict the aesthetic liberties of a façade and further cannot be used over all types of substrates such as marble or glass.

Nanoparticle based biocides such as silver, titanium dioxide (TiO_2), silicon dioxide and copper have also been commonly used as biocides due to their antimicrobial properties [17]. Photocatalytic coatings such as TiO_2 cut dirt build-up on building facades; due to its self-cleaning, anti-bacterial, anti-viral, fungicidal, anti-soiling properties. TiO_2 is also both acid and alkali resistant and is harmless to humans [18–26]. The hydrophilic and oxidation properties of these nanoparticle biocides can further inhibit biological growth on façade surfaces, potentially making it a long term solution [27–30]. While significantly fewer biological growth can be expected with the use of TiO_2, complete prevention cannot be expected [31]. Hydrophobic surfaces, on the other hand, where water droplets form and cause to repel down are also proposed as biological growth mitigation solutions as they reduce the water presence on façades. Additionally, the "non-adhesive" effects of hydrophobic surfaces can prevent spores from attaching to the surface [32].

2. Materials and methods

2.1. Sampling and experimental setup

Tropical cities such as Singapore experiences relatively high precipitation and humidity all year-round, resulting in buildings experiencing high amounts of water contact throughout the year. This results in buildings experiencing some form of biological growth attack or microbial growth on most building façades. The current study was conducted at a specific building in Singapore where recurring biological growth attacks were prevalent (Fig. 1). The 23,388 m^2 building façade has three different types of façade material, i.e. aluminium cladding, granite cladding and rendering materials (hereby referred to as aluminium substrate, granite substrate and concrete substrate respectively).

Six façade application systems were selected for this study (Table 1). They were commercially available biological growth resistant coating products chosen for their material properties such as water vapour permeability, water absorption, surface texture, colour, resistance to chemical attacks and resistance to biological growth; which determine the susceptibility of biological growth on the substrate materials considered at the site [3].

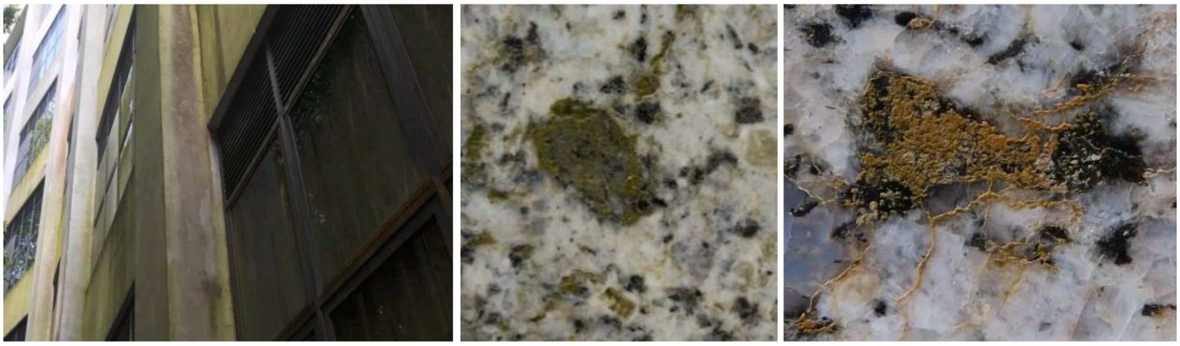

Fig. 1. Biological growth on external façade.

Table 1

Physical and chemical properties of selected products (as derived from suppliers, subject to change).

Criterion	Product					
	Product A	Product B	Product C	Product D	Product E	Product F
Properties	Self-sanitize coating solution; Superhydrophobic; self-cleaning with rain from low adhesion properties of dirt particles; Ultra durable bonding with surface; reduced wettability with water; natural protection against algae and fungi	Anti-algae/anti-microbial; water-based topcoat that can be independently used as an anti-algae coating	Durable self-cleaning effect Highly effective against algae and fungi (biocide) 100% biodegradable Easy application	Hydrophobic/oleophobic effects; stain resistant; algae growth prevention; reduce corrosion	Hydrophilic coating; self-cleaning of exterior surfaces reducing affinity dust, dirt accumulation;	Superhydrophobic; Low toxicity bacterial, fungal and algal wash; Fungistat (prevent growth of fungi rather than killing)
Areas of application	Almost any surfaces; including fabrics, wooden furniture, glass windows, plastic, laminated surfaces and ceramics	Ceramic tiles, roof tiles, marble, granite, stone, concrete, masonry and other mineral surfaces	Exterior walls; tiles, bricks, aluminium cladding, cobblestones, etc.	Glass, steel, metal, electronic boards, and automotive parts	Cladding, painted surfaces, tiles, stone, ceramic, signage, aluminium, chromed steel, most plastic surfaces; not compatible with glass	Paint, ceramics, glass, unsuitable to be applied on metallic surfaces
Substrates applied to in current study	Granite, concrete rendering, aluminium cladding	Granite, concrete rendering, aluminium cladding	Granite, concrete rendering, aluminium cladding	Granite, concrete rendering, aluminium cladding	Granite, concrete rendering, aluminium cladding	Granite, concrete rendering
Ingredients	Includes Titanium Dioxide (TiO$_2$)	Includes Titanium Dioxide (TiO$_2$)	Not advised	Perfluorobutane Sulfonate (PFBS) technology	Not advised	Biocidal product based on benzalkonium chloride and orthophenyl phenol
Appearance	Transparent	Transparent	Transparent	Transparent	Translucent	Clear
Solvent	None	Water	Water (1:3–1:6)	Water	Water	Water (1:10)
Surface coats	1 coat	3 coats	1 coat	1 coat	1 coat	2 coats
Curing period	not advised	2 days	2 days	not advised	not advised	2 days
Estimated life span	3 years	3 years	3 year	3 years	3 years	3 years
Coverage	0.02 L/m^2	0.04 L/m^2	0.125 L/m^2	0.15 L/m^2	0.04 L/m^2	0.25 L/m^2
Price	S$ 178.30/L	S$ 53.33/L	S$ 14.00/L	S$ 51.95/L	S$ 28.13/L	S$ 26.00/L

Concrete façade on-site is finished with a layer of plaster and paint. Concrete being porous, readily absorbs moisture during rain through capillary sorption and upon saturation; which can form layers of dirt that can assist biological growth. Natural stones such as granite and marble are durable and aesthetically pleasing. They are porous by nature and hence allow dirt to be retained in their pores. With surface treatment such as sealing and polishing, their water absorptivity reduces, and the formation of stain streaks may be slowed down. Aluminium facades in particular show more ease of staining due to its light colour and the design of the facades. Stain streaks form primarily after light rainfalls where the accumulated dirt on the surface cannot be washed off completely. Such stain streaks can be prime habitats for biological growth to develop; such as algae spores. Aluminium has an absorption coefficient of almost zero. In this study, sampling was done to incorporate all these three substrates (see Fig. 2).

As shown in Fig. 2, The surface applications for each product were carried out by the respective suppliers according to the manufacturer's recommendations on a test sample area of 0.5 m × 0.75 m. The sample spaces were selected based on factors of orientation and sun path, accessibility, and past biological growth. Duplication of the same product samples was carried out to minimize the impact from external factors such as possible surface deformations, external environmental factors (e.g. orientation, lighting), and workmanship (i.e. manual application and mixed proportions), to the study. The selection of samples was such that all surface applications are in close proximity to maintain the same exposure conditions throughout all study surfaces. These surfaces receive direct sunlight up to 3 h each day and receive diffused sunlight all day. The concrete samples are oriented towards North West, while the granite and aluminium samples are oriented on the South and West facing façades. Prevailing on site climatic conditions are an important factor contributing to the effectiveness of bio-

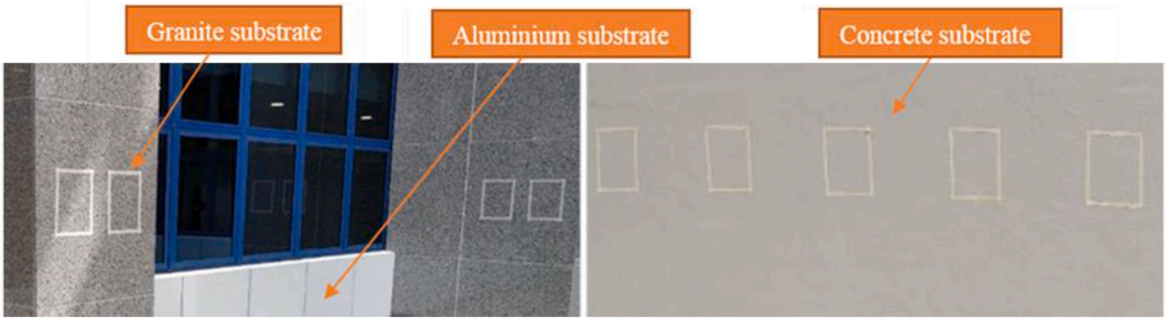

Fig. 2. Actual site set-up for biological growth resistant coatings.

logical growth resistant coatings. Due to the tropical weather conditions in Singapore, the façade experiences routine rain days with mean rain days and mean thunderstorm days over half the year; apart from the Northeast monsoon induced dry spell in February and March.

Data collection in this study was done using optical instrumentation as photogrammetric data collection methods are found to be best suited in such studies for their merits as a precise, quick, and non-contact survey technique [33]. The propagation of biological growth on façade surfaces were captured using a digital camera (Nikon D7100, 35 mm focal length). Same manual exposure settings were used to maintain the consistency of the data collected. Observations for all samples were made approximately at the same time of date (around 11am) to maintain similar exposure conditions. The photos were taken from the same viewpoint, from the same distance of 1 m from the façade surface on all instances.

In field experiments using photogrammetric data collection, one might be concerned about the differing lighting conditions experienced throughout the experiment period. However, quantitative photogrammetry analysis can still be carried out on surfaces using image processing methods by normalizing the differences in lighting conditions experienced in the field, as shown in previous studies [34]. During the current study, data collection was carried out on days with clear to slightly overcast skies to minimize any significant differences in illumination conditions. Data collected during days with heavy overcast or rain were processed out using weather records to account for outliers in the data.

2.2. Digital image processing procedure

After six months of visual observations, different characteristics of each sample surfaces were identified. Based on the experimental setup, each surface application and its respective control surfaces were exposed to the same environmental conditions over the same period. Since all surface applications considered in the study are self-cleaning coating products, it is assumed that the façade surfaces would remain free of any staining, soiling or dirt accumulation during the observation period of the study, except for the biological growth on the surfaces. Any soiling not caused by biological growth is controlled by rain and light cleaning (using no chemicals and scrubbing). Therefore, it was hypothesized that any difference in the rate of biological growth on each surface should be due to the biological growth resistive ability of the surface applications, which can then be identified using digital image processing. The thoroughly cleaned sample surfaces with no biological growth (i.e. *Day 0*) is presented in Fig. 3. Photographs from Day 1, Day2, … *Day n* of the surfaces are used to measure the effects of biological growth by comparisons to Day 0.

The digital images collated over time were put through the process illustrated in Fig. 4, the images were converted to greyscale to control the distribution of the colours and a Sobel operator was applied, improving the programming efficiency similar to the effects that of [34]. Steps 1 to 3 in Fig. 4 were carried out to cancel out any impact from varying illumination conditions. Biological growth is assumed not to have a uniform distribution on the surfaces. After step 3, the resultant gradient image (Ig) shows the amount of biological growth. The images were run through a classification algorithm in order to compute the ratio of pixels in each image indicating biological growth. The algorithm was referred from a similar photogrammetric experiment [35].

2.3. Defining a façade cleaning index

A façade substrate dependent façade cleaning index (FCI) is defined to indicate the effectiveness of biological resistant coating. This is computed using the time series data of pixel ratios showing the occurrence of biological growth on each substrate for each studied prod-

Fig. 3. Original surface conditions at Day 0.

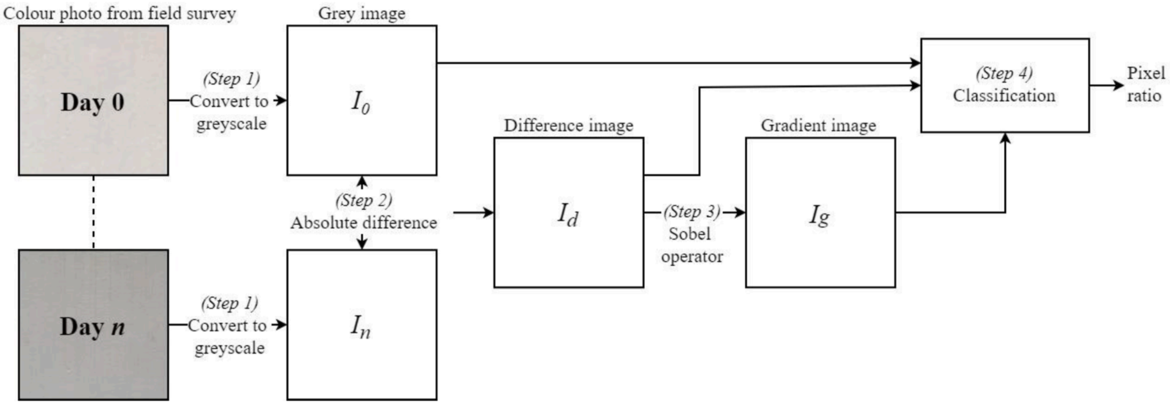

Fig. 4. Digital image processing procedure to derive the pixel ratio.

uct. For this purpose, a curve fitting exercise was carried out using a data analysis software OriginPro (version 2018b by OriginLab Corporation). The gradient of this model is defined as the FCI as it is indicative of the rate of change for biological growth over time. The results are used for a comprehensive lifecycle cost (LCC) analysis for the study building. The façade cleaning cost was based on the frequency of façade cleaning. Since the FCI differs based on the type of façade surface, the LCC were calculated for each type of façade substrate separately.

3. Results

3.1. Determining the façade cleaning index

Through image processing the illumination components from both the control and experimental surfaces are cancelled out. The output of this procedure is a pixel ratio of a surface between the Day 0 and Day n, a difference indicative of the biological growth on that surface. This process was repeated for all images to identify the trend of biological growth on all surfaces. See Figs. 5–7 for the observed pixel ratios over the study period for granite, concrete and aluminium substrates, respectively. All these curves were successfully fitted during an independent fit for this model. The residual sum of squares were all small values, indicating a tight fit of the model with the data.

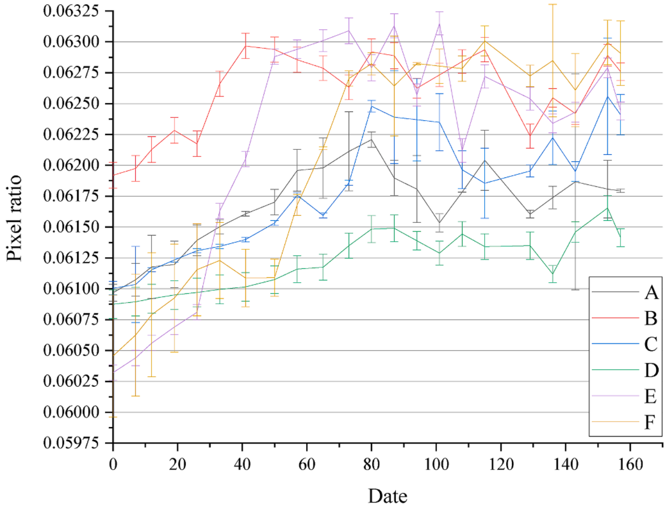

Fig. 5. Quantification of visual observation based on rule based classifications for granite substrate.

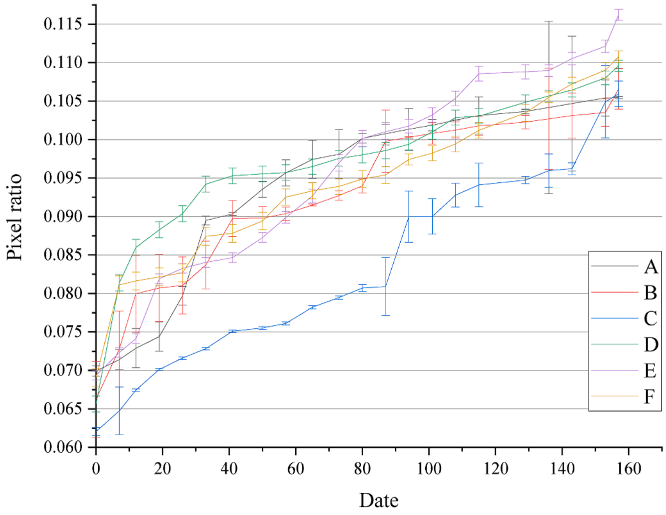

Fig. 6. Quantification of visual observation based on rule based classifications for concrete substrate.

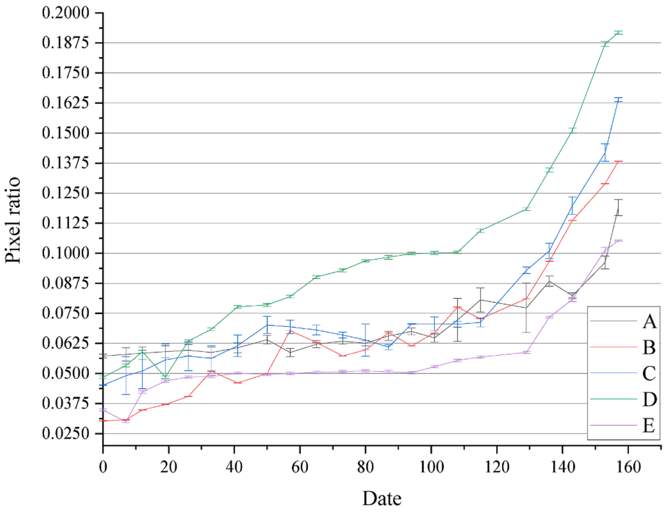

Fig. 7. Quantification of visual observation based on rule based classifications for aluminium substrate.

As seen on Fig. 7, the pixel ratios for all products are gradually increasing over time; indicating a growth of biological matter on that surface. The gradient of the model represents the rate of growth. For product A applied on aluminium substate this is 0.7269, which is the FCI for this product. Similarly, FCI values for the other product applications on each of the substrates are found in Table 2.

In Table 2, the FCI values are complemented with qualitative visual observations from the site. When comparing the qualitative and quantitative observations herein, it is found that the more effective a biological growth resistive coating is, the FCI value is lower. This index is dependent on the façade substrate and the effectiveness of the biological growth resistant coating. This index is then used to conduct a lifecycle cost (LCC) analysis for external façade cleaning at the specific building.

3.2. Economic implications of biological growth resistant coatings

In the current study, this expectation is to maintain biological growth free external façade. Comparisons are made to identify trade-offs between the lower first cost of biological growth resistant coating applications and their long term savings from variations in recurring costs. Based on the derived FCI values, the economic implications of each alternative were computed to provide decision support to decision makers. FCI values are used herein to derive the frequency of façade cleaning required for each surface applications. The resultant comparison between the achievable first year savings from each alternative is tabulated in Table 3 (see supplementary data for further details of the calculations). The 'base case' is where no biological growth resistant coating system is applied and façade cleaning is carried out as per current practice. Under the base case, two rounds of major façade cleaning is carried out annually to deal with biological growth propagation. The economic advantage of surface coatings is assumed to be the avoidance of additional cost on the removal of biological growth for the base case. To this end, cost performance of the base case with each alternative for each substrate is compared in Table 3.

As mentioned before, the FCI is used to derive how many cleaning rounds are needed in one year to keep the façade in a biological growth free state. Considering an illustrative example of aluminium substrate, if no applications are made to inhibit biological growth an annual maintenance cost of $5294.21 will incur. As presented in Table 3, if product A is used, this will be reduced by 27% to

Table 2

Quantitative and qualitative observations of biological growth on study samples.

Alternative	Granite substrate		Concrete substrate		Aluminium substrate	
	FCI	Comments from visual observations	FCI	Comments from visual observations	FCI	Comments from visual observations
Base case (Control)	NA	Severe growth	NA	Average growth, severe dirt accumulation	NA	Minimal growth, slight staining, dirt accumulated
Product A	0.6997	Minimal growth, clean surface	0.7495	Minimal growth, clean surface	0.7269	Minimal growth, clean surface
Product B	0.9705	Severe biological growth	0.7534	Minimal growth, slight dirt accumulation	0.7905	Minimal growth, slight staining, dirt accumulated
Product C	0.7003	Minimal growth, clean surface	0.7374	Minimal growth, slight dirt accumulation	0.8923	Minimal growth, severe staining
Product D	0.6655	Minimal growth, clean surface	0.8549	Average growth, severe dirt accumulation	0.9496	Minimal growth, severe staining and streaking
Product E	0.7405	Slight growth	0.8662	Average growth, severe dirt accumulation	0.6083	Minimal growth, clean surface
Product F	0.9352	Average biological growth	0.8631	Average growth, severe dirt accumulation	(Product F incompatible on aluminium substrates)	

Key: percentage biological growth on sample surface area, minimal growth (<5%); slight growth (5–15%); average growth (15–25%), severe growth (> 25%).

Table 3

Biological growth resistant product options: initial and maintenance cost summary by alternatives (in Singapore dollars (S$)).

Alternative	Application cost	Annual cleaning cost	First year savings against base case (savings in S$/%)	
Aluminium substrate				
Base case	5,294.21	5,294.21	NA	NA
Product A	37,067.64	3,848.20	1,446.01	27%
Product B	32,041.56	4,185.08	1,109.14	21%
Product C	30,696.75	4,724.26	569.95	11%
Product D	51,895.05	5,027.49	266.72	5%
Product E	28,504.13	3,220.58	2,073.64	39%
Granite substrate				
Base case	3,529.48	3,529.48	NA	NA
Product A	24,711.76	2,469.73	1,059.74	30%
Product B	21,361.04	3,425.51	103.96	3%
Product C	20,464.50	2,471.69	1,057.78	30%
Product D	34,596.70	2,348.94	1,180.54	33%
Product E	19,002.75	2,613.47	916.00	26%
Product F	31,573.80	3,300.73	228.75	6%
Concrete substrate				
Base case	14,117.90	14,117.90	NA	NA
Product A	98,847.04	10,582.00	3,535.90	25%
Product B	85,444.16	10,636.36	3,481.55	25%
Product C	81,858.00	10,410.96	3,706.94	26%
Product D	138,386.80	12,069.25	2,048.65	15%
Product E	76,011.00	12,228.50	1,889.40	13%
Product F	126,295.20	12,185.44	1,932.46	14%

$3848.20. On the other hand, if product B is used, the savings are only 21% against the base case. Product A has better first year savings against the base case due to its lower FCI, however, product B is cheaper to apply due to its lesser price.

4. Discussion

The economic implications are computed based on the notion that there can be many alternatives to meet a buildings' user expectations to an acceptable degree; whilst having different initial and recurring costs. The LCC analysis was conducted to assess the effectiveness of the different façade coating products into the perspective of a facility manager. Although a facility manager may be attracted to the performance of a certain biological growth resistant coating, he or she must also consider the long-term and immediate costs involved before deciding on which coating system to choose for the building. In the case of aluminium substrates, according to the LCC analysis, product D had the highest cumulative total cost, followed by product A, product B, product C and, lastly, product E. Product E was found to be the better alternative with having the lowest initial cost from all alternatives and promises the highest percentage savings from the annual cleaning costs. This application, which is a hydrophilic surface coating; shows minimal staining and streaking with comparisons to the control surface. It is observed that this coating is good for inhibiting biological growth as well as keeping off streaking due to its self-cleaning properties. On the other hand, product D is observed to be economically inviable due to high LCC. This is due to the higher application cost and the higher maintenance cost, resulted by its higher FCI.

According to the LCC analysis on granite surface applications, products F and D have the highest cumulative total costs, followed by product A, product B, product C and, lastly, product E. Whilst the best product to inhibit biological growth on granite was found as the product D, it had a higher total cost due to its considerably higher initial cost. The product B was found to have no much effect on this surface. However, it was found to be better than leaving the granite surfaces untreated over the course of the façade lifespan. The hydrophilic product E showed some biological growth (lesser in intensity than of the nearby control surface). However, over the lifetime of the façade, it too can be a better alternative than leaving the granite surface untreated. Both product A and product C were found to be highly effective at controlling biological growth at the site; with relatively low application costs. However, since product A is a hydrophobic coating and product C being a biocidal coating, other factors such as durability of the coatings and environmental considerations such as runoff of toxins need to be also considered in picking an alternative. As hydrophobic and hydrophilic coating systems can deliver similar results on inhibits biological growth, as a biocidal coating, the additional benefits of self-cleaning properties can also be considered.

Considering the LCC analysis for concrete façade surface applications, the results are similar to the applications on other two substrate types; where product D exhibited the highest cumulative total cost, followed by product F, product A, product B, product C and, lastly, product E. However, considering the visual observations, all surface applications were found to be relatively ineffective to consistently keep the concrete surfaces clean. It was observed that all the study surfaces were susceptible to some degree of dirt accumulation, and even slight growth of black mould in certain cases. Even so, products A, B and C did have some degree of effect on inhibiting biological growth when compared to the control surfaces. Other alternatives did not have any significant difference to the control surface from the observations made. Although there are some savings against the base case for these products, due to the relatively higher cost of application the LCC savings can be negative.

The summary of the findings of the study on effectiveness of commercially available biological growth resistant coatings are tabulated in Table 4.

Given the LCC savings, the product E hydrophilic coating shows most promise for aluminium substrates to inhibit biological growth, as well as to maintain a stain free surface. For granite substrates, either the product B or the product E hydrophilic coating can be considered based on their similar LCC performances. While the untreated surface performs best during the LCC analysis for the concrete substrates, it can be recommended to use either the biocidal product B or hydrophilic coating product E on these surfaces to inhibit biological growth and maintain the aesthetic appearance on site.

In terms of simple payback, it was found that none of the coating systems can compete with the base case of the traditional method of cleaning. Although the products do not manage to reach the payback period with the base case in this study, it is inaccurate to conclude that none of the products is viable for use. Product D has the highest cumulative total cost when applied to granite substrate, but it also has the best performing FCI. Recommendations can be drawn to aid decision makers as to which systems best suits the specific buildings in a tropical setting based on this economic baseline. The findings from the current study contribute to the improvement of facility managers' budget utilization on façade cleaning and surface repair by forecasting the performance of surface coating alternatives for different types of façade substrates. Depending on the decision-maker, elimination of biological growth may be perceived to be of higher value than the costs involved. Looking at the results, there was no single product that consistently ranked best across all substrate types. Therefore, the findings of this study can be used by facility managers to assess their decisions before committing to a single strategy for preventing biological growth on their building façades.

Use of commercially available surface applications did not fully stop biological growth and propagation but delay the undesired effects of biological growth. It was further observed that two samples of the same generic chemical product did have varying effects on slowing down the biological growth; albeit not significantly large variations. Façade surface cleaning still needs to be carried out. Therefore, the total reliance on a prohibitive chemical solution cannot be expected. Combinations of different strategies and technologies during building design and operations are required to further subdue biological growth propagation. Further research can be carried out on the effectiveness of such strategies; complemented with an understanding of the root causes of biological growth on different façade surfaces. The method proposed in this paper can be used by building professionals to compare the effectiveness of these different strategies and applications by collecting photographic data. An online platform would be developed to analyse the collected data, making it easier for facility managers to use this method without the need of an algorithm expert.

On the other hand, facility managers are not required to choose the product that performs the best in all conditions. Other considerations such as an acceptable degree of biological growth can be considered. This degree of acceptance may vary from building to building, as such an alteration to the visual aesthetics of the building will affect the sellability of the building and is also affected by tenant expectations. Depending on the purpose of the building (e.g. that of a manufacturing factory versus that of an upscale financial building), the visual aesthetics of the building will have differing importance and degree of acceptance of how clean the façade must be. This will be dependent on the branding of the building, building occupants and even public opinion. Thus, the degree of acceptance is also dependent on other variables and will require future survey-type research methods to further explore. Such future research can explore the perceived weight of the different factors contributing to the selection of a building coating system; considered by facility managers and related industry professionals.

Table 4

Summary of performance of product in inhibiting biological growth.

Substrate	Products ranking in descending order	Comments
Aluminium	E, A, B, C, D	Product E clearly stands out with significant difference from the second.
Granite	D, A, C, E, F, B	The difference between the first four products appears insignificant.
Concrete	C, A, B, F, D, E	The difference between all six products appears insignificant.

5. Conclusions

This paper investigates the effectiveness of commercially available façade coating products to inhibit biological growth on three different building substrates under tropical conditions. Specific conclusions of this paper are;

- Site observations affirmed the products used in the study had a positive effect on keeping the surfaces cleaner than the untreated façade surfaces on the aluminium and granite substrates.
- These surface applications can not completely stop biological growth but delays the undesired effects of biological growth.
- Façade surface cleaning still needs to be carried out, albeit in a lesser frequency; depending on the type of product coated.
- Sample products applied on duplicate samples had varying effects on certain surfaces. Proper cleaning prior to surface application, and close supervision and quality control during the surface application is urged to ensure the best performance of any of these products.
- Proposed method of identifying pixel ratios is useful on sunny days. During highly overcast rainy days was found to interfere with the consistency of the results.
- Proposed method has limitations when using in non-uniform surfaces such as the granite substrates, as indicated by the relatively small pixel ratio values and the relatively erratic trends of observed biological growth. Future work is proposed to overcome this limitation of this method.
- Due to the limitations of the current assumption that the digital images showcase biological growth without any instances of surface soiling; further improvements to be made by distinguishing surface soiling from biological growth during data collection.

CRediT authorship contribution statement

Ashan Senel Asmone: Methodology, Software, Formal analysis, Writing - original draft, Visualization, Project administration. **Michael Yit Lin Chew:** Supervision, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101377.

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