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Variações na aplicabilidade da termografia infravermelha para a detecção de manifestações patológicas em diferentes revestimentos de fachada: uma revisão sistemática

Vanessa Ayanna de Souza Costa
M.Sc., UPE-POLI, Brazil
Vanessa.ayanna@gmail.com
https://orcid.org/0000-0001-5463-6344

Victor Henrique Vieira Braz
Master's Student, UPE-POLI, Brazil
Victorbraz.obras@gmail.com
https://orcid.org/0000-0003-1255-0571

Girlândia de Morais Sampaio
M.Sc., UPE-POLI, Brazil
girlandiasampaio@yahoo.com
https://orcid.org/0000-0001-7804-0959

Yeda Vieira Póvoas
Professor, PhD, UPE-POLI, Brazil
yvp@poli.br
https://orcid.org/0000-0003-1907-415X

Alberto Casado Lordsleem Júnior
Professor, PhD, UPE-POLI, Brazil
acasado@poli.br
https://orcid.org/0000-0003-3276-0621

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Variações na aplicabilidade da termografia infravermelha para a detecção de manifestações patológicas em diferentes revestimentos de fachada: uma revisão sistemática

RESUMO

Objetivo – Identificar as variações na aplicabilidade da termografia infravermelha (TIR) para a detecção de manifestações patológicas em diferentes revestimentos de fachada, identificando desafios e tendências na área.

Metodologia – Foi conduzida uma Revisão Sistemática da Literatura (RSL) baseada no protocolo PRISMA. A seleção considerou 43 artigos, a partir da análise de 394 estudos importados via uma string de busca nas bases Science Direct, Scopus e Portal da CAPES, entre 2018 e 2024.

Originalidade/relevância – O estudo se insere na lacuna teórica referente à aplicação da TIR na inspeção de fachadas com diferentes tipos de revestimento, destacando-se como uma ferramenta de diagnóstico não destrutivo. A relevância acadêmica está na sistematização das variáveis que afetam a confiabilidade da técnica, considerando distintos materiais de revestimento e fatores ambientais.

Resultados – A pesquisa identificou que a TIR é amplamente empregada na inspeção de revestimentos cerâmicos, argamassados e de pedra, sendo menos frequente no concreto armado. A eficácia da técnica é influenciada por fatores como radiação solar, umidade e emissividade dos materiais. Para otimizar os resultados, recomenda-se uma diferença mínima de 10°C entre os ambientes interno e externo. Além disso, técnicas complementares, como radar de penetração no solo (RPS) e processamento avançado de imagens, são necessárias para aumentar a confiabilidade da detecção de anomalias.

Contribuições teóricas/metodológicas – O estudo evidencia os desafios da aplicabilidade da TIR em diferentes revestimentos, destacando que: (i) no cerâmico, a porosidade e a umidade influenciam a detecção; (ii) no argamassado, a heterogeneidade do material impacta os resultados; (iii) no de pedra, a variabilidade mineralógica interfere na análise; e (iv) no concreto armado, a absorção térmica elevada pode mascarar anomalias. Além disso, ressalta a importância de condições ambientais controladas e do uso de técnicas complementares para maior precisão.

Contribuições sociais e ambientais – A aplicação da TIR na manutenção preventiva de fachadas contribui para a gestão sustentável das infraestruturas urbanas, possibilitando inspeções não destrutivas e o monitoramento contínuo do estado de conservação das edificações.

PALAVRAS-CHAVE: Termografia infravermelha. Revestimento. Manifestações patológicas. Revisão sistemática.

Variations in the applicability of infrared thermography for detecting defects in different facade coatings: a systematic review

ABSTRACT

Objective – Identify variations in the applicability of infrared thermography (IRT) for detecting defects in different façade coatings, identifying challenges and trends in the field.

Methodology – A Systematic Literature Review (SLR) was conducted based on the PRISMA protocol. The selection included 43 articles, analyzed from 394 studies imported using a search string in the Science Direct, Scopus, and CAPES Portal databases, covering the period from 2018 to 2024.

Originality/Relevance – The study addresses the theoretical gap regarding the application of IRT in façade inspections with different types of coatings, highlighting its role as a non-destructive diagnostic tool. The academic relevance lies in the systematization of variables that affect the technique's reliability, considering different coating materials and environmental factors.

Results – The research identified that IRT is widely used for inspecting ceramic, mortar, and stone coatings, with less frequent application in reinforced concrete. The technique's effectiveness is influenced by factors such as solar radiation, humidity, and material emissivity. To optimize results, a minimum temperature difference of 10°C between

ISSN 2318-8472, v. 13, n. 90, 2025

indoor and outdoor environments is recommended. Additionally, complementary techniques such as ground-penetrating radar (GPR) and advanced image processing are necessary to enhance the reliability of defect detection.
Theoretical/Methodological Contributions – The study highlights the challenges of IRT applicability in different coatings, emphasizing that: (i) in ceramic coatings, porosity and humidity affect detection; (ii) in mortar coatings, material heterogeneity impacts results; (iii) in stone coatings, mineralogical variability interferes with analysis; and (iv) in reinforced concrete, high thermal absorption can mask defects. Furthermore, it underscores the importance of controlled environmental conditions and the use of complementary techniques for greater accuracy.
Social and Environmental Contributions – The application of IRT in façade preventive maintenance contributes to the sustainable management of urban infrastructure, enabling non-destructive inspections and continuous monitoring of building conservation status.

KEYWORDS: Infrared thermography. Coating. Defects. Systematic review.

Variaciones en la aplicabilidad de la termografía infrarroja para la detección de defectos en diferentes revestimientos de fachadas: una revisión sistemática

RESUMEN
Objetivo – Identificar las variaciones en la aplicabilidad de la termografía infrarroja (TIR) para la detección de defectos en diferentes revestimientos de fachada, identificando desafíos y tendencias en el área.
Metodología – Se llevó a cabo una Revisión Sistemática de la Literatura (RSL) basada en el protocolo PRISMA. La selección incluyó 43 artículos, analizados a partir de 394 estudios importados utilizando una cadena de búsqueda en las bases de datos Science Direct, Scopus y el Portal CAPES, cubriendo el período de 2018 a 2024.
Originalidad/Relevancia – El estudio aborda la laguna teórica sobre la aplicación de la TIR en la inspección de fachadas con diferentes tipos de revestimiento, destacándose como una herramienta de diagnóstico no destructivo. Su relevancia académica radica en la sistematización de variables que influyen en la confiabilidad de la técnica, considerando distintos materiales de revestimiento y factores ambientales.
Resultados – La investigación identificó que la TIR se emplea ampliamente en la inspección de revestimientos cerámicos, de mortero y de piedra, siendo menos frecuente en el hormigón armado. La efectividad de la técnica está influenciada por factores como la radiación solar, la humedad y la emisividad de los materiales. Para optimizar los resultados, se recomienda una diferencia mínima de temperatura de 10°C entre los ambientes interno y externo. Además, se identificó la necesidad de técnicas complementarias, como el radar de penetración terrestre (RPT) y el procesamiento avanzado de imágenes, para mejorar la confiabilidad en la detección de defectos.
Contribuciones Teóricas/Metodológicas – El estudio destaca los desafíos en la aplicabilidad de la TIR en diferentes revestimientos, enfatizando que: (i) en el cerámico, la porosidad y la humedad afectan la detección; (ii) en el mortero, la heterogeneidad del material impacta los resultados; (iii) en la piedra, la variabilidad mineralógica interfiere en el análisis; y (iv) en el hormigón armado, la alta absorción térmica puede enmascarar defectos. Además, resalta la importancia de condiciones ambientales controladas y el uso de técnicas complementarias para una mayor precisión.
Contribuciones Sociales y Ambientales – La aplicación de la TIR en el mantenimiento preventivo de fachadas contribuye a la gestión sostenible de las infraestructuras urbanas, permitiendo inspecciones no destructivas y el monitoreo continuo del estado de conservación de los edificios.

PALABRAS CLAVE: Termografía infrarroja. Revestimiento. Manifestaciones patológicas. Revisión sistemática.

ISSN 2318-8472, v. 13, n. 90, 2025

1 INTRODUCTION

Directly exposed to external agents, facades become vulnerable to pathological manifestations that compromise their integrity and functionality. The lack of preventive maintenance, combined with prolonged exposure to climatic factors, exacerbates these conditions and favors the emergence of anomalies (Souza et al., 2018; Brito et al., 2024), which accelerates the degradation of coatings and increases the need for corrective interventions, consequently raising the costs associated with building rehabilitation (Vasconcelos et al., 2024). Thus, periodic inspection of facades is essential to meet performance requirements that ensure safety, habitability, and sustainability, as specified by the NBR 15575-1 standard (ABNT, 2024).

In this context, the use of non-destructive techniques has proven effective for the early diagnosis of anomalies and the prevention of severe damage. Among these techniques, infrared thermography (IRT) stands out due to its ability to identify both superficial and subsurface defects, such as cracks, delaminations, water infiltrations, and efflorescence (Garrido et al., 2022; Alexakis et al., 2024; Bersch et al., 2021; Donato et al., 2021; Fort et al., 2022; Mendes et al., 2022). These anomalies can be detected by the temperature difference between the affected areas and the adjacent regions, resulting from the presence of voids or moisture that alter the heat flow (Bauer et al., 2018).

The application of IRT as an inspection tool offers significant advantages, such as rapid data collection and the possibility of remote, real-time measurements (Tanaka; Pavon, 2021), and it can even be integrated with an unmanned aerial vehicle (UAV) (Silva et al., 2021) to reach greater heights and allow for a detailed diagnosis (Albuquerque et al., 2024). However, its effectiveness depends on variables such as the camera's thermal resolution, the distance between the equipment and the inspected surface, and the environmental conditions during image capture.

Infrared thermography can also be used to perform a thermographic scan via oblique aerial flight to indicate the effects of urban vegetation on thermal regulation, thereby identifying areas with higher thermal loads due to reduced tree cover or areas with greater solar radiation attenuation (Costa et al., 2022).

Despite the advantages offered by IRT, many factors influence thermographic inspections, such as the type of camera used, the angle of incidence on the target, the emissivity of the materials, and the climatic conditions. Furthermore, the accuracy of thermographic measurements is directly related to equipment calibration, the consideration of material emissivity, and adaptation to the environmental conditions at the time of image capture (Kowalski; Masiero, 2020; Yang; Guo; Li, 2023). The orientation of facades can also impact the degradation of coatings, with variations in the presence of dirt, moisture, and delamination depending on exposure to the sun and wind (Saruhashi et al., 2024; Nascimento et al., 2024). Understanding these factors and their impact on the inspection of different types of coatings is essential for improving the reliability of the technique.

Thus, this research contributes to advancing the use of thermography in the context of detecting pathological manifestations in facade coatings, with an emphasis on building inspection and maintenance, by identifying, through a Systematic Literature Review (SLR), the

ISSN 2318-8472, v. 13, n. 90, 2025

variations in the applicability of IRT for detecting pathological manifestations in different facade coatings, highlighting challenges and trends in the field.

2 Method

This research presents a Systematic Literature Review (SLR) conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method (Moher et al., 2010; Zlatar; Kohlmanrabbani; Barkókebas Jr, 2019) with the aid of Rayyan software. The SLR aimed to answer the following question: What are the main variations in the applicability of infrared thermography for detecting pathological manifestations in different types of facade coatings? The study was developed in three main stages: planning, by developing the research protocol; execution, by searching for and selecting articles; and summarization, by analyzing and processing the data, with a synthesis of the main evidence found on the topic.

The searches were carried out in the Science Direct, Scopus, and CAPES Portal databases, aiming to obtain a diverse sample of studies. The following search string was employed: "((“facade” OR “façade”) AND (“infrared” OR “thermography”) AND (“damage” OR “defect” OR “problem”) NOT (“energyefficiency” OR “thermalcomfort”))", with filters applied as shown in Table 1.

Box 1 – Filters Used in the Research

Filter Type	Specification
Time Period	2018-2024
Document Type	Research articles only
Study Area	Civil Engineering
Language	Portuguese and English

Source: Prepared by the authors.

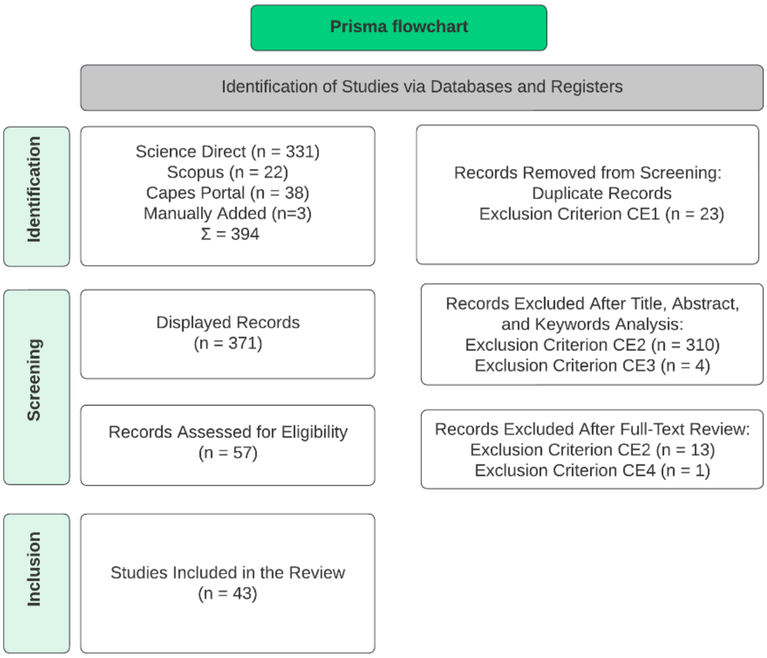
The inclusion/exclusion criteria were established to ensure the relevance of the articles. CI1: articles that use thermography for detecting pathological manifestations in facade coatings; CE1: duplicate articles; CE2: articles that do not use thermography for detecting pathological manifestations in facade coatings; CE3: review articles; CE4: works not fully available in the searched scientific databases.

In total, 394 articles were imported, of which 391 were retrieved using the search string and 3 were manually added due to their relevance. In the eligibility phase, after reading the titles and abstracts, the exclusion criteria were applied, resulting in 28 articles being categorized as "maybe." After resolving discrepancies, 57 articles remained. In a second screening, 14 studies were discarded after full-text review, leaving a total of 43 articles selected for the SLR. The process followed the PRISMA Flow Diagram (PRISMA, 2020), as illustrated in Figure 1.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 13, n. 90, 2025

Figure 1 – Article Selection Process



Source: Prepared by the authors.

3 Resultas and discussions

The results were organized into two categories: (i) the temporal and geographical distribution of publications, and (ii) the analysis of the applicability of IRT in different types of facade coatings.

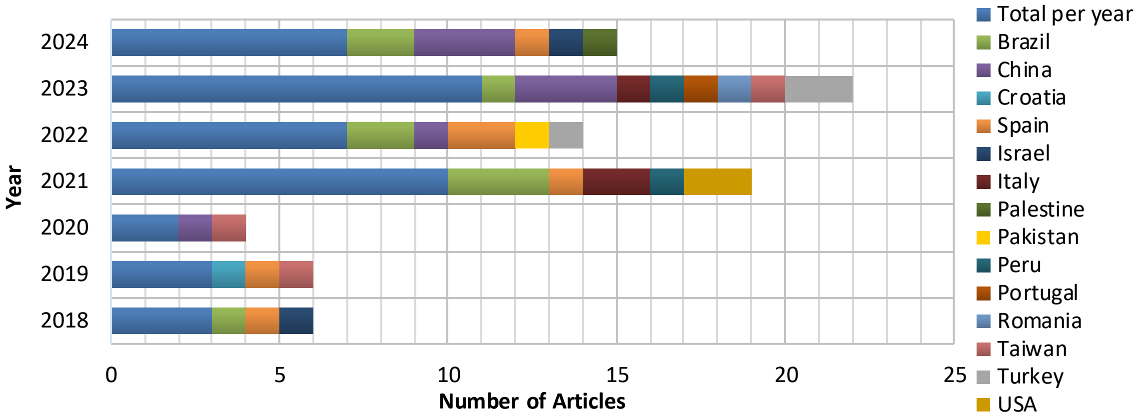
3.1 Temporal and Geographical Distribution of Publications

O gráfico da Figure 2 apresenta a distribuição das publicações. Houve um aumento significativo nos estudos nos últimos quatro anos, indicando um crescente interesse na técnica. Brasil e China lideram as pesquisas, seguidos por Itália, Espanha e Portugal. Essa tendência sugere o crescente interesse global pela aplicação da TIR, com maior representatividade de países em desenvolvimento, onde a técnica tem potencial significativo para monitoramento e manutenção de infraestruturas.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 13, n. 90, 2025

Figure 2 – Temporal and Geographical Distribution of Publications (2018–2024)



Source: Prepared by the authors.

3.2 Variations in the Applicability of Infrared Thermography in Different Types of Facade Coatings

When analyzing the percentage distribution of materials inspected using infrared thermography, there is a slight predominance of ceramic coatings, which account for 32% of the occurrences (16 studies). In contrast, mortar and stone coatings each represent 30% (15 studies), showing very similar frequencies. Reinforced concrete, on the other hand, has the lowest application at 8% (4 studies). These results underscore the versatility and importance of IRT in identifying anomalies across various types of facade coatings. It is worth noting that some articles address more than one type of coating, and this percentage difference may be related to the need for complementary techniques when dealing with coatings of greater thickness and heterogeneity.

In general, the studies highlight that environmental factors most significantly impact the ability to detect thermal anomalies, with solar radiation, wind, relative humidity, ambient temperature, and shadows being particularly influential. These elements can interfere with the thermal gradients necessary for precise anomaly identification. Frequently, IRT must be complemented by other techniques to validate the obtained results. Moreover, the studies suggest that environmental factors affect anomaly detection, recommending a minimum temperature difference of 10°C between indoor and outdoor environments to optimize the technique.

3.3 Ceramic Coatings

Aguilar et al. (2023) found that the porosity of ceramic tiles significantly impacts the detection of anomalies via thermography. More porous tiles (with a red backside) exhibited greater thermal contrast during periods of intense solar radiation, facilitating the identification of delaminations and moisture. Conversely, less porous tiles (with a beige backside) enhanced detection at the onset of heating and during cooling (Aguilar *et al.*, 2023).

ISSN 2318-8472, v. 13, n. 90, 2025

When comparing the behavior of ceramic coatings in response to delamination and moisture anomalies, Aguilar et al. (2023) observed that the average thermal contrast in moist areas, both during heating and cooling, was higher than in areas with delamination. This is attributed to water's capacity to store and release heat, indicating that the detection of moisture-related anomalies is more sensitive to temperature variations, especially in more porous materials.

After 3 hours of solar exposure, the temperature gradient between the internal and external regions reaches peaks that favor anomaly detection due to increased thermal contrast. However, during periods of high temperature (40°C), this contrast decreases considerably, making anomaly identification more challenging (Bauer; Milhomem; Aidar, 2018).

Passive thermography demonstrated the ability to detect cracks up to 5 cm in depth, although its effectiveness diminishes for deeper defects, underscoring the need for high-sensitivity equipment in such cases (Bauer; Milhomem; Aidar, 2018). Regarding delamination under dry conditions, the analysis by Tanaka and Pavón (2021) revealed that differences in the width of the delaminations significantly increase the probability of anomaly detection, while depth does not have a relevant impact on the Delta T values.

Shadows interfere with uniform thermal excitation, complicating anomaly detection. To mitigate this issue, Huang *et al*. (2020) proposed a multiplicative model which, when combined with image segmentation, enables the identification of subtle temperature variations even with a reduced delta T between 0.2°C and 0.3°C, ensuring greater precision in delineating defects on facades with ceramic coatings. Huang, Chen, and Chiang (2023) expanded this approach by integrating Robust Principal Component Analysis (RPCA) with image segmentation to further enhance detection robustness under varying shadow conditions.

Micelli and Cascardi (2020) emphasize that although the literature acknowledges the influence of emissivity and reflectivity of ceramic tiles as well as the masking of moisture or crack signals by mortar joints these factors still present challenges to the practice of infrared thermography in ceramic coatings. Such aspects can hinder result interpretation by altering the heat distribution on the surface, thereby requiring stricter control of inspection parameters and a meticulous analysis of the obtained images.

3.4 Masonry Coatings

Due to the lower density of masonry coatings, IRT is highly effective in detecting delamination and moisture (Ferreira *et al*., 2024; Barbosa; Rosse; Laurindo, 2021). However, when it comes to more subtle anomalies, qualitative identification becomes more challenging. This may be related to the camera's low spatial resolution, coating heterogeneity, and the minimal thermal variations generated (Adamopoulos *et al*., 2021). To overcome this difficulty, Adamopoulos *et al*. (2021) conducted a detailed analysis using multiband processing by integrating images obtained from three spectral regions (infrared - IRT, visible - VIS, and near infrared - NIR) to improve anomaly detection and characterization.

Gong et al. (2024) demonstrated that the surface temperature increases proportionally with the anomaly thickness up to 11 mm; beyond this point, a thermal anomaly occurs due to

ISSN 2318-8472, v. 13, n. 90, 2025

the thermal capacity effect: the thicker cavity retains more heat, but the heat transmission is slower, resulting in lower-than-expected temperatures.

Regions with cement-based mortar exhibited significantly higher surface temperatures compared to areas coated with lime mortar (Delta T = 3°C), due to the higher thermal conductivity of cement (Batool *et al.*, 2022). The advanced deterioration of the material such as loss of cohesion, porosity, and disaggregation of the mortar was identified via thermography through increased heat absorption and retention in these areas, leading to elevated surface temperatures. This characteristic can be used to assess the conservation state of walls and to indicate regions that require immediate repair (Batool *et al.*, 2022).

In addition to the interference of external factors, the applicability of IRT in masonry coatings presents limitations that may generate false positives, including dirt, shadows (Garrido *et al.*, 2019; Ferreira *et al.*, 2024), and additional coatings, such as wooden panels and layers of paint (Batool *et al.*, 2022).

Resende *et al.* (2022) observed that solar exposure for a period of 1.5 to 3 hours was sufficient to generate adequate thermal contrasts, allowing for the detection of delamination anomalies, cracks, and areas with moisture.

3.5 Stone Coatings

Infrared thermography has proven to be a valuable tool in detecting anomalies in the coatings of historical buildings, despite the challenges imposed by the complex geometry of monuments and the heterogeneity of materials such as natural stones and mortar joints (Alexakis *et al.*, 2024; Solla *et al.*, 2024). Additional challenges include the non-uniform thickness of the coating and its mineralogical composition (Alexakis *et al.*, 2018; Briceño *et al.*, 2021; Hatır; Ince; Bozkurt, 2022; Pescari; Budau; Vilceanu, 2023). Differences in the thermal capacity and conductivity of the mineral components can create complex thermal gradients, complicating the accurate interpretation of thermograms, particularly in coatings with multiple layers or heterogeneous mixtures (Briceño *et al*, 2021).

Chacara *et al.* (2023) pointed out the limitation of IRT in detecting the depth and extent of cracks, due to insufficient solar exposure and the uniform emissivity assumed to simplify the analysis (Diz-Mellado *et al.*, 2021). To overcome this challenge, ground-penetrating radar (GPR) was employed, allowing for a more precise mapping of anomalies (Kilic, 2023; Solla *et al.*, 2024) and aiding in the investigation of subsurface conditions, such as areas potentially related to the development of infiltrations and deformations in the coatings (Diz-Mellado *et al.*, 2021). Fort *et al.* (2022), in turn, found that active thermography is effective for detecting internal anomalies in stone coatings, particularly in environments with high salt concentrations, where passive thermography presents limitations.

Granite surfaces, due to their dense composition and low permeability, exhibit less pronounced thermal variations, whereas mortar joints, because of their higher porosity, promote moisture retention, thereby intensifying the thermal contrast and facilitating its detection (Alexakis *et al.*, 2024; Solla *et al.*, 2024). Diz-Mellado *et al.* (2021) and Ozmen and Sayin (2023) indicate that the roughness of original limestone can compromise the uniformity of

ISSN 2318-8472, v. 13, n. 90, 2025

thermal images, hindering the precise identification of internal anomalies, especially in restored materials such as the volcanic tuff encountered in the study by Ozmen and Sayin (2023).

Hatır, Ince, and Bozkurt (2022) emphasize that pyroclastic rocks, due to their higher porosity, are more susceptible to deterioration processes such as freeze-thaw cycles and salt crystallization characteristics that can be effectively detected by infrared thermography. Similarly, Ozmen and Sayin (2023) found that volcanic tuff, used as a restoration material, exhibits high porosity, resulting in more pronounced thermal variations that facilitate the identification of affected areas in environments with high humidity or exposed to adverse atmospheric conditions.

High temperatures detected in thermograms indicate localized delaminations or the absence of fixing mortar behind travertine tiles, whereas lower temperatures relative to anomalously high-temperature areas suggest partial or total delaminations (Pescari; Budau; Vilceanu, 2023).

3.6 Reinforced Concrete Coatings

The few studies in this SLR that explore the application of IRT in reinforced concrete coatings do not address the specific characteristics of the technique related to this material. Nonetheless, they validate its efficiency in detecting anomalies and emphasize the influence of environmental factors such as wind, solar radiation, and temperature on detection accuracy (Zhang et al., 2020; Li *et al.*, 2022; De Filippo et al., 2023; Wang *et al.*, 2024). Li *et al.* (2022) highlight that direct solar radiation can mask temperature differences, hindering the precise detection of thermal anomalies. Although this is not unique to concrete coatings, it is particularly relevant for this material due to its high thermal absorption capacity.

The integration of IRT with UAVs and computational algorithms has proven effective in the early detection of thermal anomalies, providing greater precision and a significant reduction in analysis time. De Filippo *et al.* (2023) emphasize that, although the method yields good results in reinforced concrete coatings, further adjustments are necessary to broaden its applicability to other types of coatings.

4 CONCLUSION

This study investigated the variations in the applicability of infrared thermography for detecting pathological manifestations in different types of facade coatings. The systematic review revealed that the technique is widely used in ceramic, masonry, and stone coatings, while its application in reinforced concrete is less frequent. Its effectiveness is influenced by environmental factors, necessitating complementary strategies to ensure more precise diagnostics.

The increase in publications on the topic indicates growing interest, especially in developing countries, further establishing IRT as a promising tool for the preventive

ISSN 2318-8472, v. 13, n. 90, 2025

maintenance of buildings. Anomaly detection relies on favorable thermal conditions, with a minimum temperature difference of 10°C between the indoor and outdoor environments recommended to optimize results.

The main challenges in the applicability of IRT are: (i) in ceramic coatings, the influence of porosity and moisture; (ii) in masonry coatings, the material's heterogeneity; (iii) in stone coatings, mineralogical variability; and (iv) in reinforced concrete, the high thermal absorption.

Despite the great potential of IRT for the inspection and preservation of facades, its application presents limitations, such as shadow interference and the need for controlled environmental conditions. However, the technique stands out for its ability to support sustainable urban infrastructure management by enabling non-destructive inspections and continuous monitoring of building conservation status. The integration of IRT with other monitoring techniques and the development of more robust methodologies are essential to enhance its reliability and contribute to more efficient and sustainable maintenance practices.

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DECLARATIONS

AUTHOR CONTRIBUTIONS

- **Study Conception and Design**: Vanessa Ayanna and Girlândia Sampaio.
- **Data Curation:** Vanessa Ayanna, Victor Braz, and Girlândia Sampaio.
- **Formal Analysis:** Vanessa Ayanna, Victor Braz, and Girlândia Sampaio.
- **Funding Acquisition:** Yeda Póvoas.
- **Investigation:** Vanessa Ayanna, Victor Braz, and Girlândia Sampaio.
- **Methodology:** Vanessa Ayanna.
- **Writing – Original Draft:** Vanessa Ayanna and Victor Braz.
- **Final Review and Editing**: Vanessa Ayanna and Girlândia Sampaio.
- **Supervision**: Yeda Póvoas and Alberto Casado.

DECLARATION OF CONFLICTS OF INTEREST

We, Vanessa Ayanna, Victor Braz, Girlândia Sampaio, Yeda Póvoas, and Alberto Casado, declare that the manuscript entitled "Variations in the Applicability of Infrared Thermography for the Detection of Pathological Manifestations in Different Facade Coatings: A Systematic Review" complies with the following statements":

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3. **Personal Conflicts:** The authors have no personal conflicts of interest related to the content of this manuscript.