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Bio-Based Synthesis of Ag-Containing TiO_2 Materials Using Cassava Starch and Propolis: Enhanced Antimicrobial Activity Against *Escherichia coli*

Thamyres Rodrigues Alves[1*], Lilian Costa Alecrim[1], Stefani Pedroso da Silva[1], Luiz Eduardo Nochi Castro[2], Larissa Resende Matheus[2], Vanessa Cosme Ferreira[2], Tânia Forster-Carneiro[2], Dirlei Diedrich Kieling[1], Leda Maria Saragiotto Colpini[1,3]

[1] Federal University of Paraná, Jandaia do Sul Advanced Campus
[2] School of Food Engineering (FEA), University of Campinas
[3] Graduate Program in Environmental Engineering and Technology, Federal University of Paraná, Palotina Sector

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ABSTRACT

Bio-based approaches to advanced materials are receiving increasing attention because they enable the incorporation of renewable resources into material synthesis. In this study, Ag-containing TiO_2 materials were prepared by conventional impregnation and a modified cassava-starch-assisted sol–gel route, with and without propolis extract, and their antimicrobial activity was evaluated against *Escherichia coli* ATCC 25922. Material suspensions were prepared at 0.5% (w/v), corresponding to 0.5 g of material per 100 mL of culture medium, and incubated at 35 °C for 24 h under dark conditions, without controlled irradiation. Bacterial viability was determined by the standard plate-count method using three experimental repetitions per material, with duplicate plate counts for each repetition. Pristine TiO_2 did not differ significantly from the untreated control, whereas the Ag-containing formulations showed substantial reductions in bacterial counts. The incorporation of propolis was associated with further enhanced antimicrobial activity, with the S-P formulation showing no detectable colonies under the assay conditions, considering a detection limit of 1 CFU mL^{-1}. These findings indicate that cassava starch and propolis can be incorporated as biomass-derived components in the preparation of Ag-containing TiO_2 materials and that propolis incorporation was associated with enhanced antimicrobial performance under the conditions investigated. Further studies involving comprehensive physicochemical characterization, component-specific controls, additional microorganisms, concentration-response experiments, silver-release measurements, controlled irradiation tests, and quantitative environmental assessment are needed to clarify the mechanisms and broader applicability of these materials.

KEYWORDS Green synthesis, Antimicrobial activity, Sustainable nanotechnology, Renewable biomass

1. Introduction

The development of sustainable materials has increasingly emphasized the integration of environmental considerations into the design and production of functional materials. Sustainable chemistry seeks to address societal and technological challenges while considering the broader interactions among chemical processes, resources, energy, and environmental impacts rather than treating these aspects independently (Anastas and Zimmerman 2018). In this context, the use of renewable biomass-derived components in material synthesis has attracted interest as one possible strategy for developing alternative preparation routes for functional materials.

Titanium dioxide (TiO_2) is one of the most extensively studied metal oxides because of its chemical stability and its established applications in photocatalysis. TiO_2-based materials have been investigated for processes involving pollutant degradation, antimicrobial activity, and self-cleaning

* Corresponding author. Email address: thamyresrodrigues078@gmail.com (Thamyres Rodrigues Alves)

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surfaces, particularly because photocatalytic reactions can promote the formation of reactive species under light irradiation (Fujishima *et al.* 2008; Banerjee *et al.* 2015). However, the photocatalytic response of TiO_2 is strongly dependent on irradiation conditions, and its activity is influenced by factors such as light absorption and recombination of photogenerated charge carriers (Fujishima *et al.* 2008; Ran *et al.* 2023). Accordingly, modification of TiO_2 with other components, including silver, has been investigated as an approach for altering its functional properties. Reported Ag-containing TiO_2 systems have exhibited antimicrobial activity under different experimental conditions, including conditions with and without intentional light irradiation (Allahverdiyev *et al.* 2011; Zarzzeka *et al.* 2024; Zarzzeka *et al.* 2025).

Silver-based materials are of particular interest because silver-containing species have well-documented antimicrobial activity against a broad range of microorganisms. The antimicrobial effects described in the literature include interactions with bacterial membranes, disturbance of cellular processes, protein modification, oxidative stress, and effects associated with the release of Ag^+ ions (Rai *et al.* 2009; Dakal *et al.* 2016; Siddiqi *et al.* 2018). These properties have stimulated the development of Ag-containing oxide materials for antimicrobial applications. Nevertheless, the preparation of silver-containing materials may involve chemical reagents and processing conditions that motivate the search for alternative synthesis strategies based on renewable or bio-derived components (Iravani 2011; Ahmed *et al.* 2016; Radulescu *et al.* 2023).

Green synthesis approaches have been investigated as alternatives for the preparation of metal and metal oxide nanomaterials, particularly through the use of plant-derived materials and other biological resources. Plant extracts, polysaccharides, and other biomass-derived compounds may participate in metal-ion reduction, complexation, stabilization, or other stages of material formation, depending on their composition and the synthesis conditions (Iravani 2011; Salem and Fouda 2021; Radulescu *et al.* 2023). However, the use of a biological component in a synthesis route should not, by itself, be interpreted as evidence of lower environmental impact, since the overall environmental performance of a process also depends on factors such as energy demand, solvent use, processing conditions, and waste generation.

Among biomass-derived materials, propolis is of particular interest because of its complex composition and documented biological activity. Propolis is a resinous bee product containing diverse classes of compounds, including flavonoids, phenylpropanoids, terpenoid-related compounds, and other constituents whose composition can vary according to botanical and geographic origin (Huang *et al.* 2014). Its antibacterial activity has been extensively investigated, with reported effects varying according to the chemical composition of the extract and the microorganism evaluated (Przybyłek and Karpiński 2019; Zulhendri *et al.* 2021). Propolis has also been investigated as a biological resource for metal nanoparticle synthesis. Roy et al. (2010), for example, demonstrated that propolis extracts and selected propolis constituents could mediate the formation of silver and gold nanoparticles under alkaline conditions. More recent literature has continued to investigate the relationship between propolis extraction and its application in silver-containing nanomaterial synthesis (Mançano *et al.* 2025).

Cassava starch is another biomass-derived material of interest for modified sol–gel synthesis. It is a renewable and biodegradable polysaccharide that has been investigated as a low-cost component in the preparation of oxide materials. Ferreira et al. (2016) reported the use of cassava starch as a chelating agent in the sol–gel synthesis of CeO_2 nanoparticles. Almeida et al. (2020) investigated a tapioca-assisted sol–gel route for ZnO nanopowders and reported smaller crystallite sizes when cassava starch was incorporated into the synthesis. These studies demonstrate the use of cassava starch as a biomass-derived component in sol–gel routes for oxide synthesis.

Of particular relevance, Zarzzeka et al. (2026) recently reported the preparation of Ag/TiO_2 materials through a modified sol–gel route using tapioca as a gelling agent. That study investigated Ag loadings of 2 and 10 wt% and included physicochemical characterization by FTIR and XRD, as well as antibacterial assays performed under dark and black-light conditions. The authors identified

metallic Ag and anatase phases in the characterized materials and reported antibacterial activity against *Escherichia coli* and *Staphylococcus aureus* under the evaluated conditions (Zarzzeka *et al.* 2026).

The present study is related to this recent line of research but addresses a different formulation strategy. Here, propolis extract is incorporated together with cassava starch in the preparation of Ag-containing TiO_2 materials, and the effect associated with propolis incorporation is examined using both a conventional impregnation route and a modified starch-assisted sol–gel route. The propolis extract was obtained by pressurized liquid extraction, a strategy recently investigated for the recovery of bioactive compounds from Brazilian brown propolis (Matheus *et al.* 2026). The study therefore focuses on the preparation of Ag-containing TiO_2 materials using biomass-derived components and on the comparison of their antimicrobial performance under the experimental conditions investigated.

Accordingly, this study aimed to prepare Ag-containing TiO_2 materials by conventional impregnation and by a modified cassava-starch-assisted sol–gel route, with and without propolis extract, and to evaluate their antimicrobial activity against *Escherichia coli* ATCC 25922. The observed differences among the formulations were used to assess the association between propolis incorporation, synthesis route, and antimicrobial performance under the experimental conditions investigated.

2. Materials and methods

2.1. Materials

Titanium dioxide (TiO_2, Êxodo Científica) was employed as the inorganic support for the preparation of the investigated Ag-containing materials. Silver nitrate ($AgNO_3$, Sigma-Aldrich) was used as the silver precursor for the incorporation of silver-containing species into the TiO_2-based materials. Cassava starch was selected as a renewable biopolymeric gelling agent, while propolis extract was employed as a natural reducing and bioactive medium, in accordance with a green synthesis approach. All reagents were analytical grade, and ultrapure Milli-Q water was used throughout the experiments.

2.2. Impregnation method (I)

Prior to synthesis, TiO_2 was dried at 120 °C for 21 h to remove adsorbed moisture and improve dispersibility in aqueous media. Ag-containing TiO_2 materials were prepared via an impregnation route using $AgNO_3$ solution corresponding to a nominal elemental Ag loading of 10 wt% in the final TiO_2–Ag composition (adapted from Colpini *et al.* 2014). In a typical procedure, 30 g of pre-dried TiO_2 was dispersed in 30 mL of ultrapure Milli-Q water under mechanical stirring until a homogeneous suspension was obtained. Subsequently, an aqueous $AgNO_3$ solution, prepared by dissolving 5.2477 g of $AgNO_3$ in 12.4 mL of ultrapure Milli-Q water, was added under continuous agitation to promote uniform distribution of Ag^+ species over the TiO_2 surface. The resulting suspension was maintained under rotational stirring (120 rpm) for 17 h at room temperature to ensure effective metal–support interaction. Thereafter, the excess solvent was removed by vacuum evaporation using a rotary evaporator under heating at approximately 80 °C. The obtained solid was dried at 120 °C for 21 h and subsequently calcined with a heating ramp at 400 °C for 5 h. The sample was designated as I.

2.3. Sol-gel synthesis/green synthesis (S)

Titanium dioxide, used as the support material for the preparation of Ag-containing TiO_2 material, was initially dried in an oven at 120 °C for 21 h. The material was synthesized using a modified sol–gel route employing cassava starch as a gelling agent, adapted from the methodologies described by Almeida *et al.* (2020), Ferreira *et al.* (2016), and Zarzzeka *et al.* (2026). Briefly, 5 g of tapioca starch were dispersed in 150 mL of distilled water under continuous stirring. Subsequently, a previously prepared suspension containing TiO_2 (30 g) and silver nitrate ($AgNO_3$, 5.2477 g) in 50 mL of distilled water was

slowly added to the starch solution. The resulting mixture was heated at 80 °C for 1 h to obtain a homogeneous and viscous gel. The final suspension was concentrated using a rotary evaporator maintained at approximately 80 °C. To obtain the xerogel, the material was dried in an oven at 100 °C for 24 h and subsequently calcined with a heating ramp at 400 °C for 5 h. The material was prepared using a nominal elemental Ag loading of 10 wt% in the final TiO_2–Ag composition.

2.4. Propolis extraction by pressurized liquid extraction

Raw propolis was supplied by a local producer in northern Paraná State, Brazil. Prior to extraction, the material was dried at 35 °C for 24 h and stored under dark and dry conditions until further use. The extraction process was performed using a semicontinuous pressurized liquid extraction (PLE) system (Figure 1). The extraction reactor had a capacity of 110 mL and was coupled to a high-performance liquid chromatography (HPLC) pump (Teledyne SSI, model SSI 12 × 6, State College, PA, USA). The extraction solvent was preheated before entering the reactor through a heat exchanger, ensuring that the desired extraction temperature was reached prior to contact with the sample. During the extraction process, pressure and temperature were continuously monitored using pressure gauges (0–7500 psi, accuracy ±0.1%) and K-type thermocouples (Wika, Klingenberg am Main, Germany), respectively. PLE was carried out at a constant pressure of 200 bar, a solvent flow rate of 5 mL min^{-1}, and an extraction time of 30 min. Extract aliquots were collected at 5 min intervals throughout the extraction. The solvent-to-feed (S/F) ratio was 60 g of solvent per gram of propolis. A pressure of 200 bar was selected to maintain the extraction solvent in the pressurized liquid state throughout the investigated temperature range while ensuring stable and safe operating conditions. The extraction conditions used in this study were 65% (v/v) ethanol in water, an extraction temperature of 120 °C, and a solvent pH of 2.

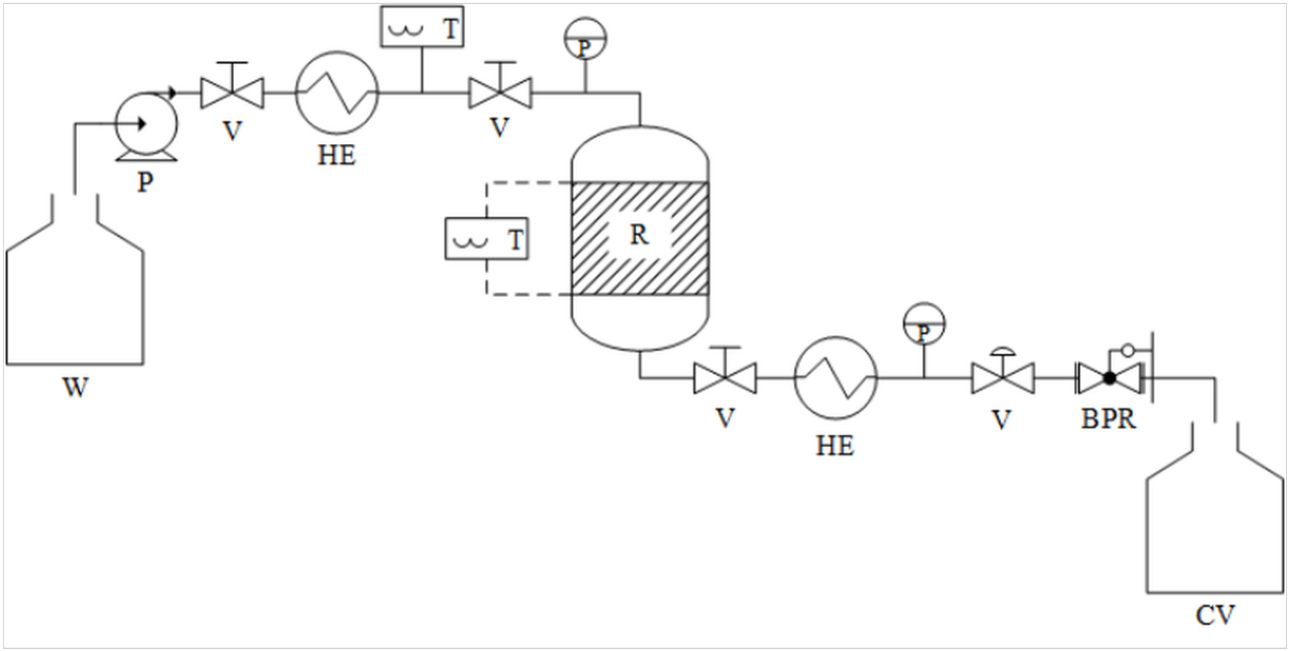

Figure 1. Schematic representation of the semicontinuous pressurized liquid extraction (PLE) system employed for the extraction of raw propolis. The system consists of a solvent reservoir, high-pressure pump, heat exchanger, extraction reactor, pressure control unit, and collection vessel operating under controlled temperature and pressure conditions. Label: W, water tank; p, high-pressure pump; V, block valves; P, manometer; T, thermocouples; R, extraction reactor; HE, heat exchanger; MV, micrometric valve; CV, collecting vessel.

2.5. Impregnation method using propolis (I-P)

The Ag-containing material was prepared using a nominal elemental Ag loading of 10 wt% in the final TiO_2–Ag composition. For the synthesis, 15 g of pre-dried TiO_2 were dispersed in 30 mL of propolis extract, whose pH was adjusted to 10 using 0.1 mol L^{-1} NaOH, forming a homogeneous paste. Next, 2.6240 g of the metal precursor silver nitrate ($AgNO_3$, Sigma-Aldrich), previously dissolved in the same extract, was added. The resulting suspension was mechanically stirred for 30 minutes to ensure complete homogenization. Subsequently, the excess solvent was removed by evaporation at 50 °C until a solid material was obtained (Castro *et al.* 2022).

2.6. Sol-gel synthesis/green synthesis using propolis (S-P)

A modified sol–gel route was implemented using cassava starch as a biopolymeric structuring agent and propolis extract as the liquid medium for material preparation (Figure 2). Cassava starch (5 g) was dispersed in 30 mL of propolis extract previously adjusted to pH 10 using 0.1 mol L^{-1} NaOH to enhance colloidal stability and precursor reactivity. Under continuous mechanical stirring, TiO_2 (15 g) and the $AgNO_3$ (2.6240 g) precursor were sequentially introduced into the system. Stirring was maintained for 30 min until a homogeneous viscous sol was obtained, resulting in a viscous mixture before drying. The resulting sol was dried at approximately 50 °C to induce controlled gelation and solvent removal, leading to the formation of a xerogel precursor (adapted from Almeida *et al.* 2020 and Ferreira *et al.* 2016).

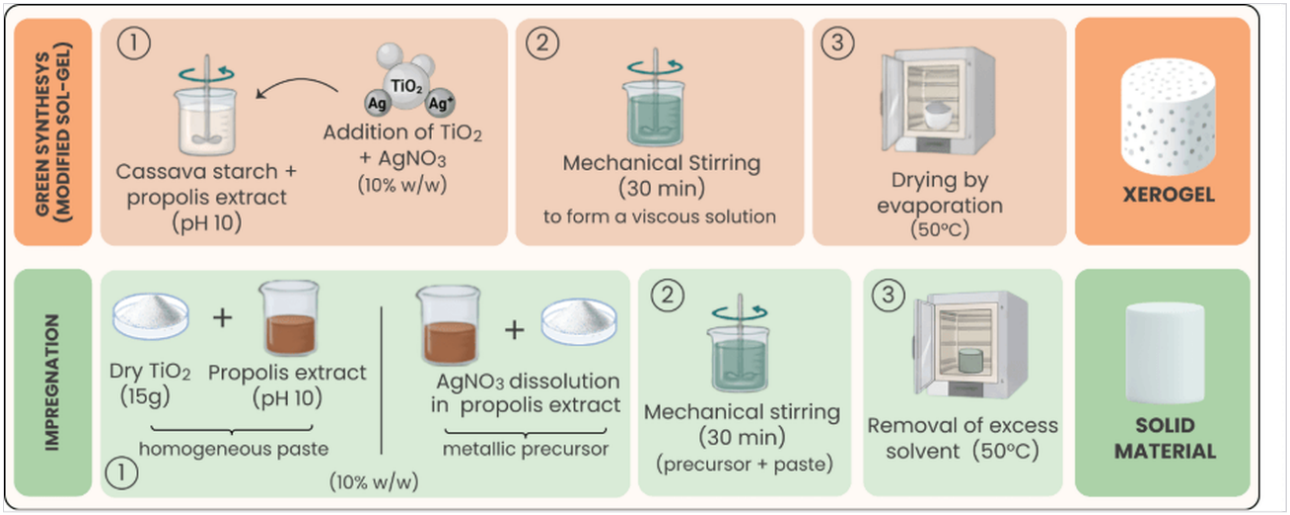

Figure 2. Schematic representation of the two Ag-containing TiO_2 synthesis routes investigated in this study. The upper panel illustrates the modified starch-assisted sol–gel process using cassava starch and propolis extract as biomass-derived components, leading to xerogel formation. The lower panel illustrates the conventional impregnation route, including preparation of the $AgNO_3$ precursor solution, mechanical stirring, solvent removal, and formation of the Ag-containing TiO_2 material.

2.7. Preparation of the bacterial inoculum

The strain used in the antimicrobial activity tests was *Escherichia coli* (ATCC 25922), cryopreserved in glycerin. To activate the cryopreserved strain, 200 µL of bacterial suspension was inoculated into test tubes containing 5 mL of Brain Heart Infusion (BHI) broth. The tubes were incubated at 35 °C for 24 h. After incubation, the bacterial suspension was diluted in saline solution (NaCl 9 g L^{-1}) to adjust the turbidity to 0.5 on the McFarland scale, equivalent to a concentration of 1 to 2 × 10^8 CFU·mL^{-1}. From this adjusted suspension, successive dilutions (1:10) were performed in saline solution (9 g L^{-1} NaCl) until the bacterial suspension used as an inoculum in the antimicrobial activity test was obtained, with a concentration of 10^4 CFU mL^{-1}. All materials used in the analyses, as well as culture media and solutions, were prepared and sterilized in advance.

2.8. Antimicrobial activity assay

Antimicrobial activity was evaluated against *Escherichia coli* ATCC 25922 as a representative Gram-negative bacterial strain (Figure 3). The bacterial inoculum was prepared as described in Section 2.7 and adjusted to a final concentration of 10^4 CFU mL^{-1}. Material suspensions were prepared in BHI broth at a concentration of 0.5% (w/v), corresponding to 0.5 g of material per 100 mL of culture medium, and inoculated with the standardized bacterial suspension at 10^4 CFU mL^{-1}. Sample preparation and inoculation were performed under ambient laboratory light. The inoculated samples were incubated at 35 °C for 24 h in a closed incubator under dark conditions, without an intentional or controlled irradiation source. Following incubation, aliquots were serially diluted in sterile saline solution and plated onto Plate Count Agar (PCA). Plates were incubated at 35 °C for an additional 24 h. Colonies capable of forming visible colonies under the specified incubation conditions were counted and expressed as CFU mL^{-1}. The detection limit of the plate-count procedure under the experimental conditions was 1 CFU mL^{-1}. Antimicrobial activity was assessed based on the reduction in bacterial viability relative to the untreated control. The assay was conducted according to established microbiological procedures for broth-based antimicrobial evaluation, and viable cell enumeration (Balouiri *et al.* 2016). Three experimental repetitions were performed for each material using a homogeneous sample preparation. For each experimental repetition, bacterial enumeration was performed in duplicate, resulting in two technical plate counts per experimental repetition. Thus, the three experimental repetitions constituted the experimental replicates, whereas the duplicate plate counts were considered technical measurements.

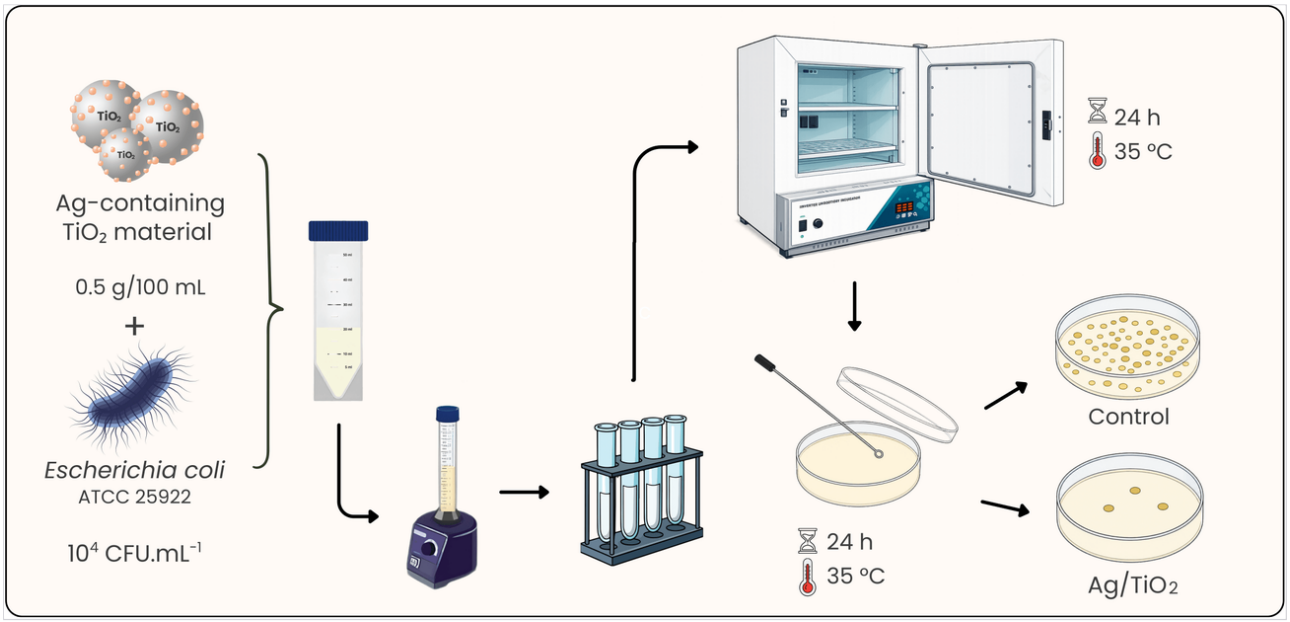

Figure 3. Schematic illustration of the antimicrobial activity assay performed against *Escherichia coli* (ATCC 25922). Material suspensions were inoculated with the bacterial culture, incubated under the specified experimental conditions, serially diluted, plated on Plate Count Agar (PCA), and incubated for colony-forming unit (CFU) enumeration.

2.9. Statistical analysis

Three experimental repetitions were used for each material, and differences among groups were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's post hoc test. Differences with a p-value < 0.05 were considered statistically significant. Data are presented as mean values with the corresponding uncertainty shown in Figure 4. Statistical analyses were performed using Statistica 7.0 software (StatSoft Inc., Tulsa, OK, USA).

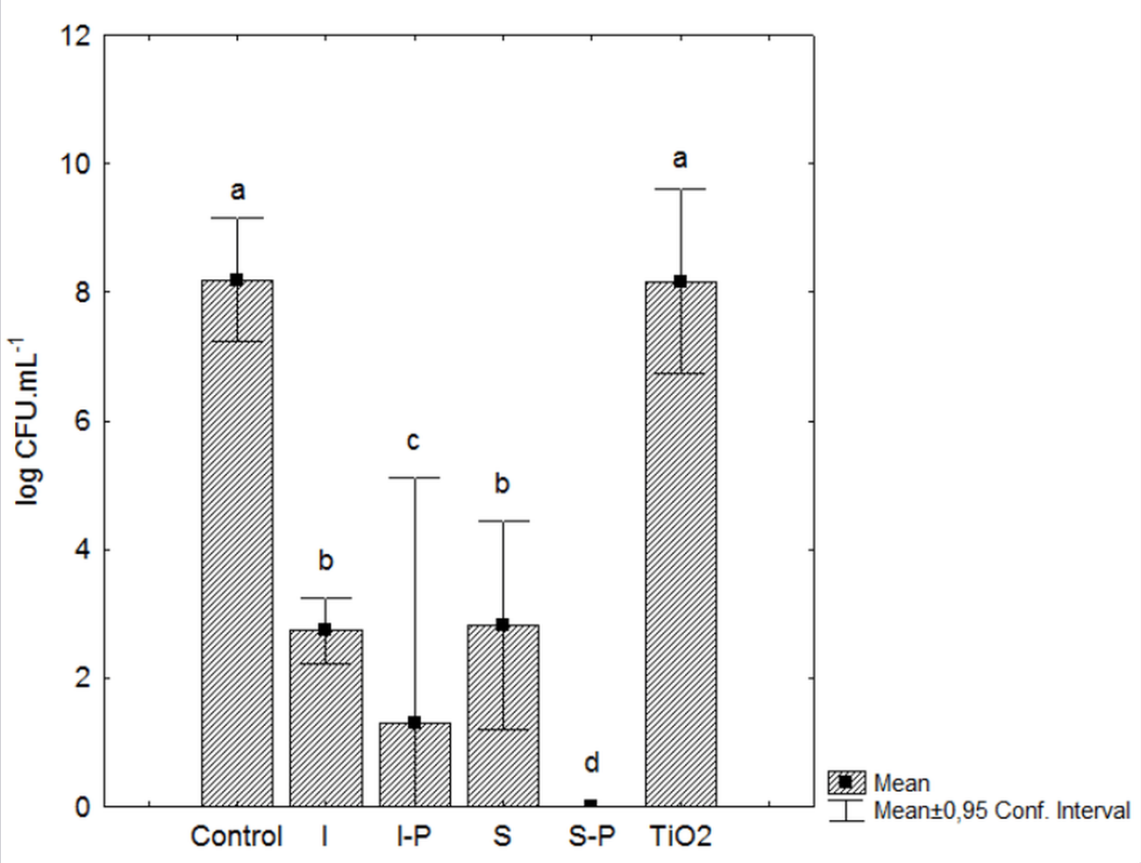

Figure 4. Antimicrobial activity of the synthesized Ag-containing TiO_2 materials against *Escherichia coli* ATCC 25922 expressed as log CFU mL^{-1} after 24 h of incubation. Different letters indicate statistically significant differences (ANOVA followed by Tukey's test, $p < 0.05$). Error bars represent the 0.95 confidence interval.

2.10. Biosafety statement

Escherichia coli ATCC 25922 was handled in accordance with the biosafety and laboratory safety procedures established by the institution. No institutional biosafety approval was required for this work.

3. Results and discussion

3.1. *Antimicrobial activity of the* Ag-containing TiO_2 materials

The antimicrobial activity of the investigated Ag-containing TiO_2 materials against *Escherichia coli* ATCC 25922 is presented in Figure 4. Significant differences ($p < 0.05$) were observed among the evaluated samples. Under the experimental conditions used in this study, pristine TiO_2 did not significantly reduce bacterial viability compared with the untreated control. In contrast, the Ag-containing formulations showed marked reductions in bacterial counts for both synthesis routes. The incorporation of propolis was associated with a further reduction in bacterial viability, with the S-P material showing the lowest bacterial recovery among the investigated formulations.

The untreated control exhibited bacterial counts close to 8 log CFU mL^{-1}, indicating substantial bacterial growth in the absence of the tested materials. Similar values were obtained for pristine TiO_2, with no statistically significant difference between these two groups. Although TiO_2 is one of the most extensively investigated photocatalytic materials due to its chemical stability, low toxicity, and oxidative properties, its photocatalytic antimicrobial activity is strongly associated with light-induced generation of electron–hole pairs (Foster *et al.*, 2011; Ran *et al.*, 2023). However, no intentional or controlled irradiation was applied during the antimicrobial assay in the present study.

Therefore, under the experimental conditions employed, the antimicrobial activity of pristine TiO_2 was insufficient to significantly reduce bacterial viability. Under illuminated conditions, the recombination of photogenerated charge carriers can limit ROS formation and consequently reduce the antibacterial efficiency of TiO_2 (Foster *et al.*, 2011; Ran *et al.*, 2023).

The Ag-containing formulations exhibited substantially lower bacterial recovery than the untreated control and pristine TiO_2. This behavior is consistent with the well-established antimicrobial activity of silver-containing materials reported in the literature. Previous studies have associated the antibacterial effects of silver-containing systems with mechanisms including Ag^+ release, interactions with bacterial membranes, protein modification, interference with intracellular processes, and oxidative stress (Dakal *et al.*, 2016; Franci *et al.*, 2015; Burdușel *et al.*, 2018). These mechanisms provide possible explanations for the reduced bacterial recovery observed in the present study. However, the specific contribution of these processes was not directly investigated.

Interestingly, no statistically significant difference was observed between the conventional impregnation and the starch-assisted sol–gel synthesis in the absence of propolis. This observation suggests that both preparation methods successfully incorporated biologically active silver species onto the TiO_2 support, producing comparable antimicrobial performance. Nevertheless, despite exhibiting similar bacterial inhibition, the two synthesis routes differ substantially regarding sustainability and processing characteristics (Doolan *et al.*, 2022; Radulescu *et al.*, 2023). The impregnation method relies primarily on the deposition of silver species onto the oxide surface, whereas the modified sol–gel approach promotes molecular-level mixing of the precursors within a biodegradable polymeric network formed by cassava starch, as schematically illustrated in Figure 5. Such structural differences become particularly relevant after the incorporation of propolis.

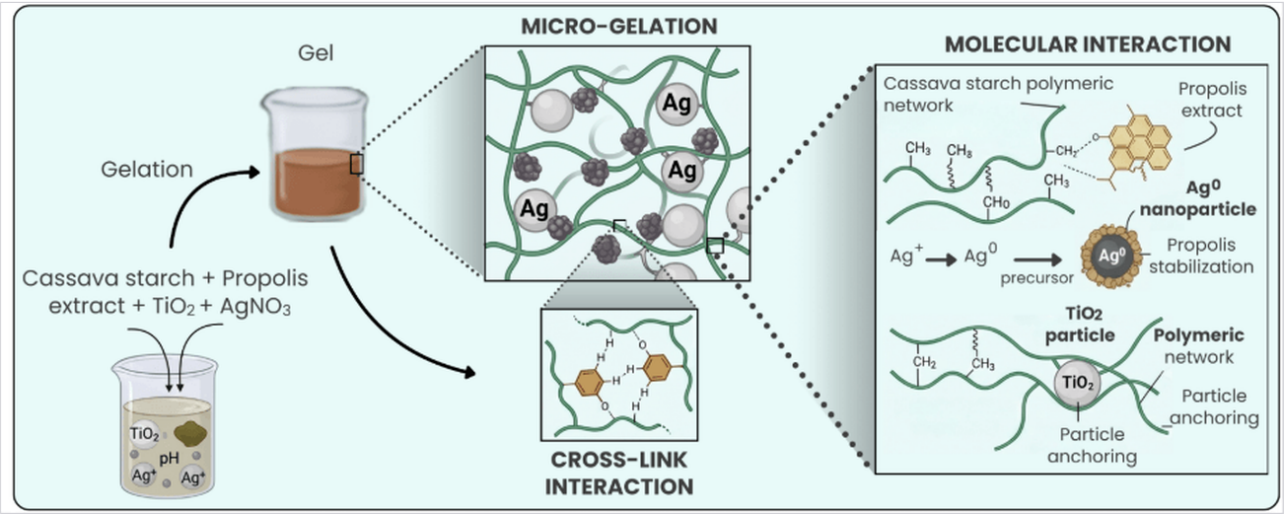

Figure 5. Conceptual representation of gel formation and possible interactions during the modified cassava-starch-assisted sol–gel synthesis. Cassava starch is represented as a biomass-derived structuring component, while propolis-derived compounds may participate in silver-ion reduction and stabilization processes. The scheme illustrates possible interactions among cassava starch, TiO_2, the silver precursor, and propolis-derived compounds during material preparation and is presented as a conceptual interpretation rather than as direct experimental evidence.

3.2. Enhanced antimicrobial activity associated with propolis incorporation

The most remarkable finding of this study was the substantial enhancement in antimicrobial activity associated with propolis incorporation. The addition of this natural bee-derived product was associated with increased bacterial inhibition regardless of the synthesis route, suggesting that propolis may contribute not only to synthesis-related processes but also to the antimicrobial performance of the resulting materials.

The impregnation sample containing propolis (I-P) exhibited significantly lower bacterial counts than the corresponding material prepared without propolis. This improvement suggests that bioactive compounds naturally present in propolis may contribute to bacterial inactivation, in addition to their possible participation in the synthesis process. However, the highest antimicrobial activity was achieved by the modified sol–gel sample synthesized in the presence of both cassava starch and propolis (S-P). No visible colonies were detected for this material under the conditions of the plate-count assay, considering a detection limit of 1 CFU mL^{-1}.

The enhanced antimicrobial response observed for S-P may be related to the combined presence of the inorganic components and the bioactive compounds present in propolis. Unlike conventional chemical reducing agents, propolis contains a highly complex mixture of flavonoids, phenolic acids, aromatic compounds, terpenoids, and other polyphenolic constituents that have been reported to participate in metal-ion reduction and stabilization processes and to exhibit antimicrobial activity (Huang *et al.*, 2014; Zulhendri *et al.*, 2021; Mançano *et al.*, 2025). Consequently, propolis may play a multifunctional role during material preparation, with possible contributions to both the synthesis process and the antimicrobial response.

The enhanced activity observed for S-P may also be associated with differences in silver distribution resulting from the modified sol–gel process. During gel formation, cassava starch may act as a biodegradable structuring agent capable of interacting with precursor species and influencing nucleation and growth (Almeida *et al.*, 2020; Ferreira *et al.*, 2016). Such effects could potentially influence the distribution of silver-containing species within the TiO_2-based material; however, this hypothesis could not be directly verified in the present study because comprehensive physicochemical characterization was not performed.

Another important aspect concerns the intrinsic antimicrobial properties of propolis itself. Numerous studies have demonstrated that flavonoids such as pinocembrin, galangin, chrysin, and caffeic acid phenethyl ester are associated with antibacterial activity and may affect bacterial membranes, metabolic enzymes, and other essential cellular processes (Zulhendri *et al.*, 2021). In addition, phenolic compounds have been associated with oxidative stress-related effects in microbial cells (Huang *et al.*, 2014; Zulhendri *et al.*, 2021). Therefore, the enhanced antimicrobial response observed for S-P may reflect the contribution of multiple components, although the specific mechanisms responsible for this response were not directly investigated in the present study.

The present findings suggest that propolis may contribute not only to the synthesis of the Ag-containing materials but also to their antimicrobial performance. Rather than being considered solely as a biomass-derived synthesis component, propolis may have a multifunctional role during material preparation and may contribute to the biological functionality of the resulting material.

4. Conclusion

This study demonstrated the preparation of Ag-containing TiO_2 materials through both conventional impregnation and starch-assisted sol–gel synthesis routes, incorporating propolis as a biomass-derived component. The use of cassava starch and propolis provided a bio-based approach to the preparation of the investigated materials.

The antimicrobial assays revealed that the incorporation of silver significantly enhanced the antibacterial performance of TiO_2 against *Escherichia coli* ATCC 25922. While pristine TiO_2 exhibited no significant antimicrobial activity under the experimental conditions, Ag-containing materials markedly reduced bacterial viability. The highest antimicrobial activity was observed for the material synthesized by the modified sol–gel method in the presence of cassava starch and propolis (S-P), for which no visible colonies were detected under the conditions of the plate-count assay, considering a detection limit of 1 CFU mL^{-1}. These findings indicate enhanced antimicrobial activity associated with propolis incorporation under the conditions investigated.

The enhanced activity observed for the S-P material may be associated not only with the well-established bactericidal properties of silver but also with the presence of bioactive compounds in

propolis. In addition, cassava starch provided a renewable biomass-derived component for the modified sol–gel route. However, the present experimental design does not allow the specific contribution of each component or the nature of their interaction to be established, and the mechanisms underlying the observed antimicrobial response were not directly investigated.

Beyond their antimicrobial performance, the synthesized materials may represent a basis for further studies on functional antimicrobial systems. Their potential applications warrant additional investigation, particularly in fields that increasingly demand durable antimicrobial performance and environmentally responsible production.

Overall, this work demonstrates that combining biomass-derived components such as cassava starch and propolis with Ag-containing TiO_2 materials provides a bio-based approach for the development of antimicrobial materials. Further studies involving comprehensive physicochemical characterization, additional microorganisms and material concentrations, silver-release measurements, controlled irradiation experiments, and quantitative environmental assessment are needed to clarify the mechanisms underlying the observed antimicrobial activity and to better assess the broader potential and sustainability of these materials.

Declarations

Author contributions. Thamyres Rodrigues Alves: Methodology, Investigation, Formal Analysis Writing – Review & Editing. Lilian Costa Alecrim: Methodology, Investigation, Formal Analysis, Writing – Original Draft, and Writing – Review & Editing. Stefani Pedroso da Silva: Methodology, Investigation, Formal Analysis, Writing – Review & Editing. Luiz Eduardo Nochi Castro: Formal Analysis, Writing – Review & Editing. Larissa Resende Matheus: Writing – Review & Editing. Vanessa Cosme Ferreira: Writing – Review & Editing. Tania Forster-Carneiro: Conceptualization, Project Administration, Supervision, and Writing – Review & Editing. Dirlei Diedrich Kieling: Conceptualization, Project Administration, Supervision, and Writing – Review & Editing. Leda Maria Saragiotto Colpini: Conceptualization, Project Administration, Supervision, and Writing – Review & Editing.

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Conflicts of interest. The authors declare no competing financial interest.

Data availability. The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics. Ethical approval and informed consent were not required because this study was based exclusively on previously published literature.

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