Enhancing Radionuclide Retention In Phosphorus-32 Plesiobrachytherapy Using Chemically Active Silica–Silicone Composites

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ABSTRACT

Phosphorus-32 (^{32}P) is a beta-emitting radionuclide suitable for plesiobrachytherapy due to its short penetration depth and localized dose delivery, making it promising for palliative spinal treatments. This study developed and characterized a flexible silica-silicone composite in which silica was chemically impregnated with phosphoric acid to improve radionuclide retention and reduce leachability. The impregnated silica was incorporated into a silicone elastomer matrix at four concentrations (0.5%, 1.0%, 1.5% and 5% w/w), and the resulting composites were evaluated for homogeneity, stability, and mechanical conformity. All formulations showed good flexibility, structural integrity, and adaptation to non-planar surfaces, with no visible swelling, cracking, or degradation during immersion or handling. These findings suggest that the proposed composite is a promising material for safe and adaptable ^{32}P plesiobrachytherapy sources, representing an advance in the development of beta-emitting brachytherapy materials.

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INTRODUCTION

Central Nervous System (CNS) cancer accounted for 3.6% of all new malignant tumor cases and approximately 2.6% of cancer-related deaths worldwide in 2022, according to the WHO [1].

Phosphorus-32 (^{32}P) is a beta-emitting radionuclide suitable for plesiobrachytherapy due to its short tissue penetration depth and ability to deliver highly localized radiation, making it a promising option for palliative spinal treatments. Polymeric ^{32}P sources are particularly attractive because their flexibility allows them to conform to irregular anatomical surfaces, improving dose distribution in intracavitary applications [2-4].

A major challenge in developing polymer-based radioactive sources is maximizing radionuclide loading while ensuring effective immobilization and low leachability. Silica is a promising inorganic carrier due to its high surface area, chemical stability, and surface silanol groups, which can be chemically modified to enhance phosphorus retention. In this study, silica was impregnated with phosphoric acid and incorporated into a silicone elastomer matrix to develop a flexible composite with improved radionuclide retention, reduced leachability, and enhanced safety for ^{32}P plesiobrachytherapy.

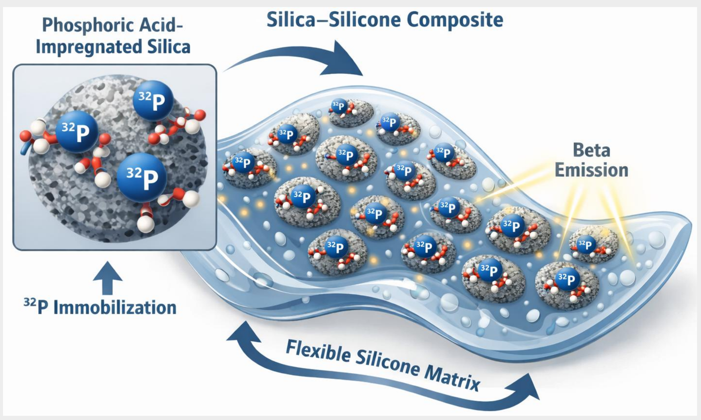

Figure 1. Schematic representation of the proposed silica–silicone composite.

METHODS AND MATERIALS

Silica particles were impregnated with phosphoric acid to promote chemical interaction between the phosphorus species and the silica surface, aiming at improved radionuclide immobilization.

The impregnated silica, previously stained with methylene blue to facilitate the visualization of its dispersion within the polymeric matrix, was incorporated into a silicone elastomer matrix using the method described in Figure 1 at four different concentrations (0.5%, 1.0%, 1.5%, and 5% w/w).

Composite matrices were prepared under controlled conditions and cured into reproducible geometries. Visual inspection and mass variation analyses were performed to assess macroscopic homogeneity and stability. Mechanical conformity was qualitatively evaluated through bending and manual handling tests simulating clinical positioning.

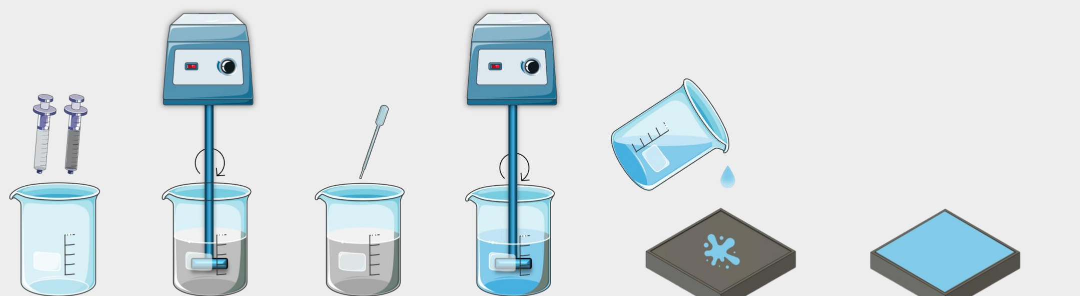

Figure 2. Schematic representation of the method used to produce the films.

RESULTS

All formulations exhibited good flexibility and structural integrity, enabling adaptation to non-planar anatomical surfaces. No visible swelling, cracking, or degradation was observed during immersion or mechanical handling.

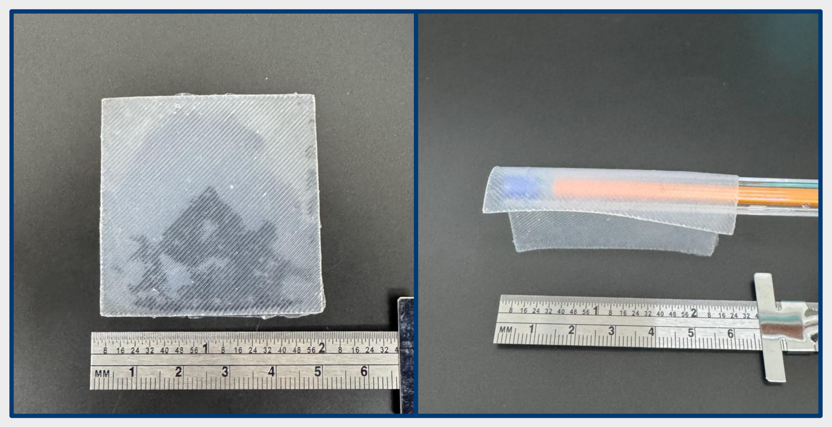

Figure 2. Sample of silicone rubber film.

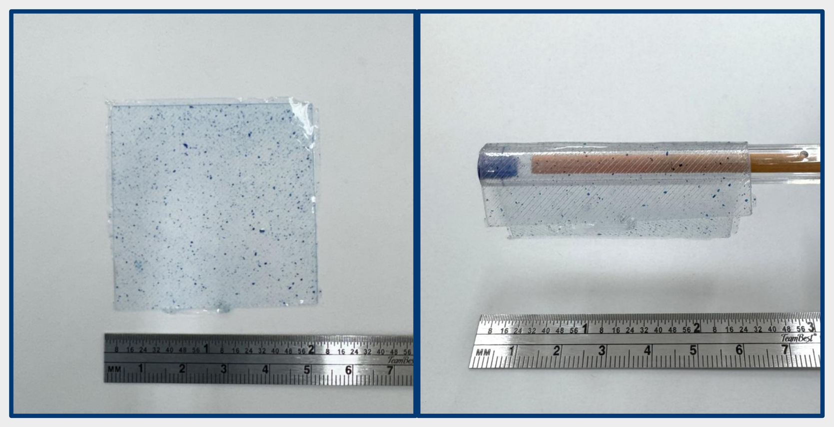

Figure 4. Sample of silica-silicone composite with 0.5% w/w.

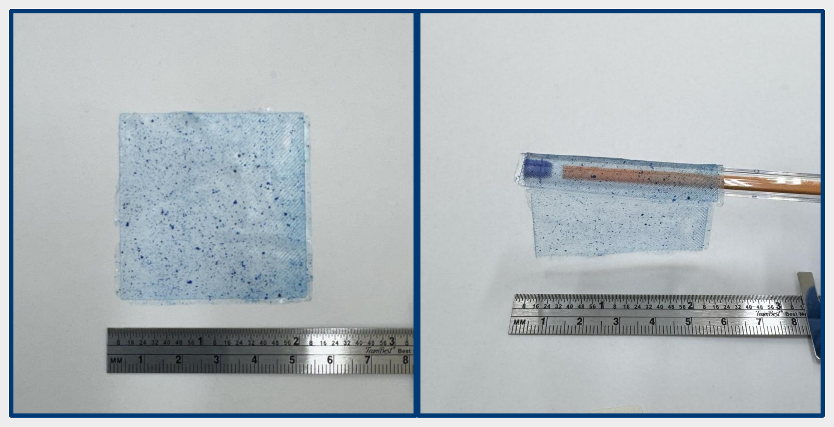

Figure 5. Sample of silica-silicone composite with 1.0% w/w.

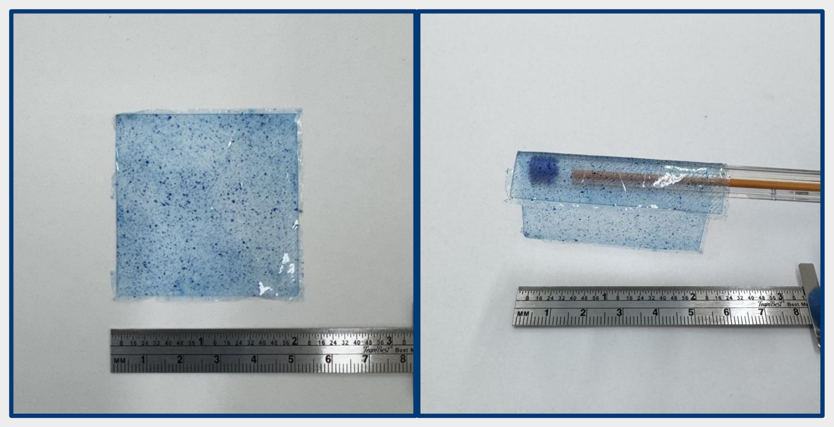

Figure 6. Sample of silica-silicone composite with 1.5% w/w.

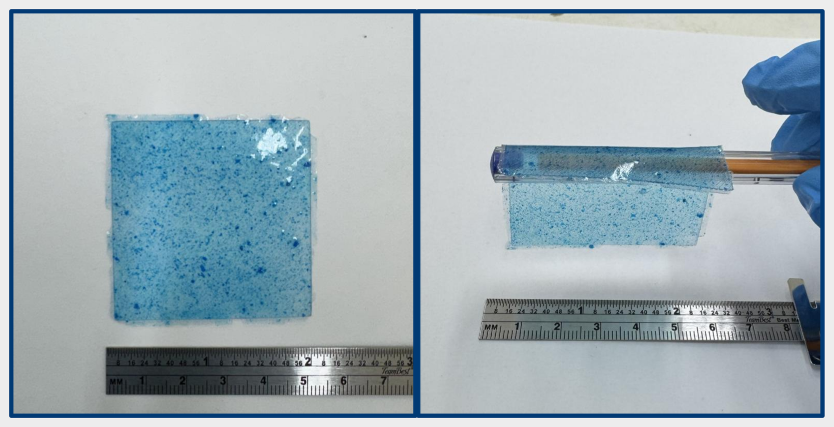

Figure 7. Sample of silica-silicone composite with 5% w/w.

Figure 8. Immersion test for samples with 0.5% and 1.0% w/w.

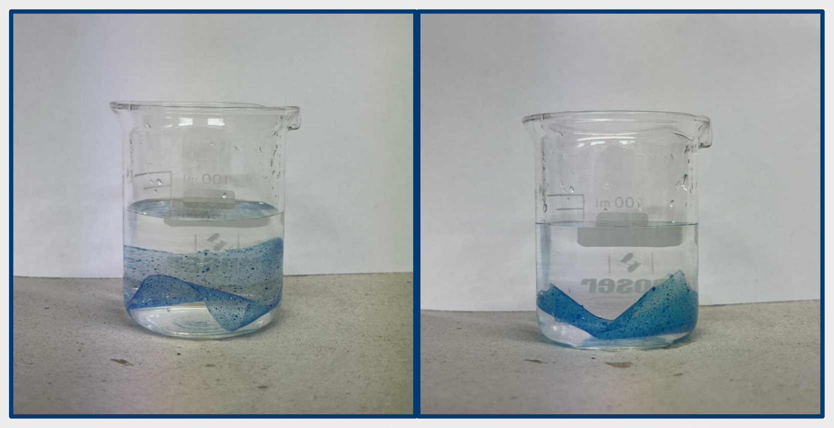

Figure 9. Immersion test for samples with 0.5% and 1.0% w/w.

DISCUSSION

The phosphoric acid-impregnated silica was successfully incorporated into the silicone elastomer without evidence of undesirable chemical interactions between the inorganic filler and the polymeric matrix. All formulations maintained flexibility and structural integrity, and no visible swelling, cracking, deformation, or degradation was observed after immersion testing, indicating that the incorporation of silica did not compromise the mechanical properties required for a conformable brachytherapy source. These findings support the feasibility of using silica as a carrier to improve radionuclide immobilization while preserving the advantages of a flexible silicone matrix.

Although the composite exhibited satisfactory performance, the addition of silica increased the viscosity of the silicone, making manual spreading into the mold more challenging and potentially affecting thickness uniformity. Future studies should investigate optimized processing methods to improve reproducibility and achieve a more uniform silica particle size distribution. The possible influence of methylene blue on particle agglomeration should also be evaluated. Radioactive validation, including neutron activation and radionuclide retention studies, could not be performed due to the scheduled maintenance of the IEA-R1 research reactor and will be addressed in future work.

CONCLUSIONS

The proposed silica-silicone composite demonstrated excellent flexibility, structural integrity, and homogeneous incorporation of phosphoric acid-impregnated silica, supporting the feasibility of this approach for the development of polymeric ^{32}P brachytherapy sources. The use of impregnated silica is expected to enhance radionuclide retention while maintaining low leachability and the mechanical conformity required for clinical application. Future studies will focus on optimizing composite processing and validating radionuclide incorporation and retention after neutron activation.

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