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Comparative Analysis of Bio-Based and Synthetic Scale Inhibitors in Geothermal Wells

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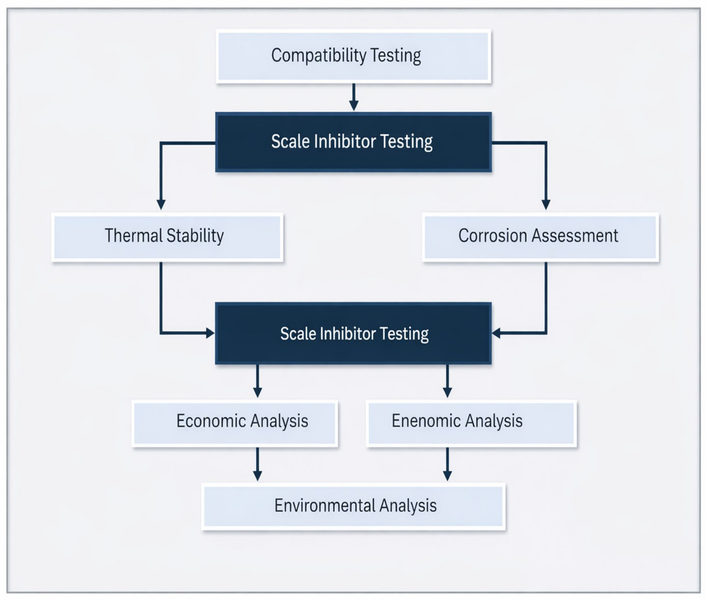
INTRODUCTION/BACKGROUND

Geothermal energy stands as one of the most reliable and sustainable renewable energy resources, offering continuous baseload power with minimal carbon emissions. However, its long-term efficiency is frequently challenged by mineral scale deposition within wells and surface facilities. Under high-temperature and high-pressure conditions, geothermal fluids rich in dissolved minerals such as silica, calcium carbonate, and metal sulfides undergo physicochemical changes that trigger precipitation (Arab and Merkel 2021). The resulting scale formation restricts fluid flow, reduces heat transfer efficiency, increases maintenance frequency, and escalates operational costs.

Scale inhibitors are widely applied (Otieno, 2026, Yan and Qi,2023) as a chemical control strategy. Traditionally, synthetic inhibitors such as phosphonates and polymer-based compounds have dominated geothermal operations due to their strong thermal stability and proven performance. Nevertheless, growing environmental concerns and stricter regulatory frameworks have intensified the search for greener alternatives. Bio-based inhibitors, derived from renewable and biodegradable materials, have emerged as promising candidates capable of reducing ecological impact while maintaining acceptable inhibition efficiency (Sutopo and Prasetyo, 2021). This comparative analysis examines the performance, environmental compatibility, and operational feasibility of bio-based versus synthetic scale inhibitors, aiming to identify sustainable and technically viable solutions for modern geothermal development.

METHODS

These methods collectively guide the selection of scale inhibitors that balance performance, safety, and sustainability in geothermal operations.



RESULTS

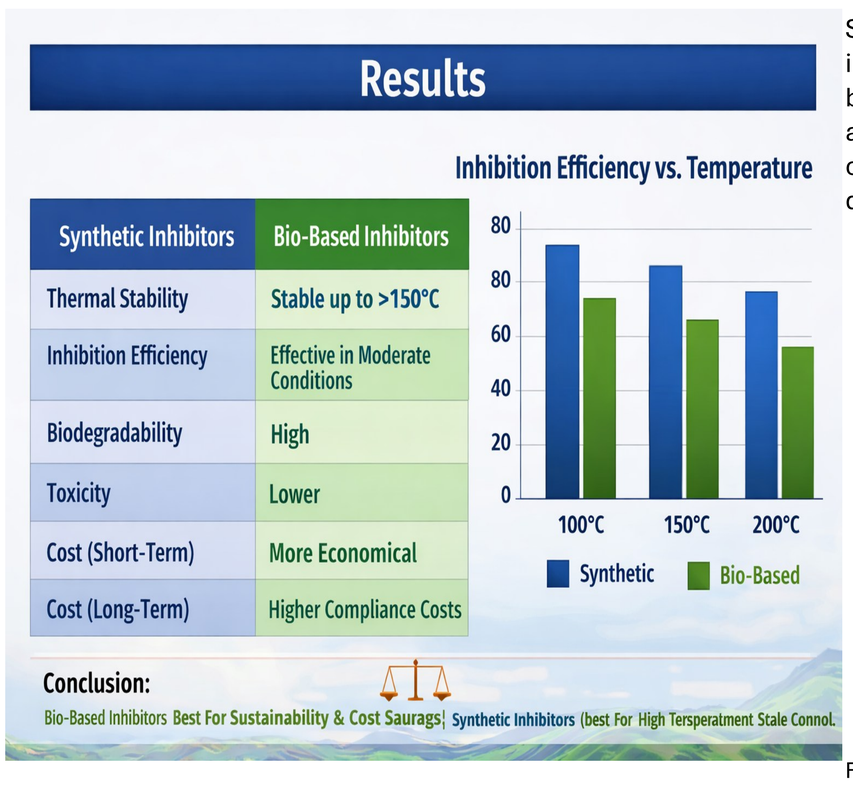


FIGURE 1. Systematic diagram showing synthetic and Bio-based inhibitors

Synthetic inhibitors generally achieve 85–95% efficiency in high temperature geothermal systems above 200°C, while biobased inhibitors perform effectively in moderate conditions with 70–90% efficiency. In terms of thermal stability, synthetics remain stable beyond 250°C, whereas biobased options begin to decline around 180–200°C. Corrosion assessments show no significant acceleration at optimized dosages, though some synthetic phosphonates can mildly interact with metals. Environmentally, biobased inhibitors stand out for their high biodegradability and low toxicity, while synthetic types may leave persistent residues in discharge streams. Economically, synthetics offer lower upfront costs, but biobased inhibitors can provide long-term savings through reduced compliance risks and alignment with sustainability regulations.

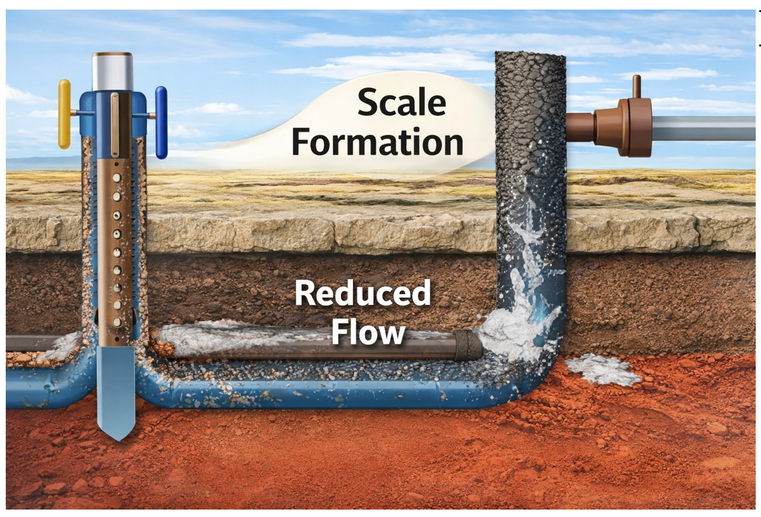


FIGURE 2. Scale formations resulted in flow reduction (Scaling results)

Category	Types of Inhibitors	Pilot/Field Applications
Bio-Based	- Polyaspartic acid (PASP, PASPProlineamide) - Polysaccharides (starch, cellulose, chitosan) etc	- Xi'an (China): PASPPro-lineamide tested in geothermal brines up to ~180–200°C - Germany: Biodegradable polysaccharide inhibitors trialed in deep geothermal wells
Synthetic	-Phosphonates (ATMP, HEDP, PBTC) -Polyacrylates and copolymers -Sulfonated polymers	- Phosphonate inhibitors deployed in geothermal power plants for carbonate/sulfate scale control -Synthetic polymer applied in geothermal wells for silica and carbonate scale

DISCUSSION

Synthetic inhibitors remain more suitable for ultrahigh enthalpy geothermal systems because of their strong thermal stability and consistent performance at extreme temperatures, often maintaining efficiency above 200°C and stability beyond 250°C. Biobased inhibitors, while less robust under such conditions, show strong potential in environmentally sensitive fields due to their high biodegradability, low toxicity, and effective scale control in moderate temperature ranges. Their performance typically declines above 180–200°C, but they remain valuable for operations where sustainability and ecological compliance are prioritized. Hybrid formulations, combining the resilience of synthetic compounds with the environmental advantages of biobased materials, may provide the optimal balance between performance and sustainability, offering both reliable inhibition and reduced ecological footprint. Corrosion assessments indicate no significant acceleration at optimized dosages, though some synthetic phosphonates can mildly interact with metals, requiring monitoring. Economically, synthetic inhibitors offer lower upfront costs, while biobased options may deliver longterm savings by reducing compliance risks and aligning with sustainability mandates. However, longterm field validation for biobased inhibitors remains limited, underscoring the need for extended trials to confirm their reliability in diverse geothermal operations.

CONCLUSION

Synthetic inhibitors demonstrate superior thermal robustness and established field reliability, making them the preferred choice for ultrahigh enthalpy geothermal systems where extreme temperatures demand proven stability. In contrast, biobased inhibitors offer environmentally sustainable alternatives with steadily improving performance, positioning them as attractive options for fields where ecological sensitivity and regulatory compliance are critical. The selection of inhibitors should always be reservoir specific, taking into account fluid chemistry, operating temperature, regulatory frameworks, and lifecycle cost considerations to ensure both technical effectiveness and economic viability. Looking ahead, future research should prioritize enhancing the thermal resistance of bio-based formulations and conducting extended field trials to validate their long-term reliability. Such efforts will be essential in bridging the performance gap between biobased and synthetic options, ultimately enabling hybrid or tailored solutions that balance operational efficiency with sustainability goals. This comparative perspective underscores the importance of aligning inhibitor choice with both reservoir conditions and broader environmental and economic priorities.

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