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A Systematic Review and Meta-Analysis of Biopolymer-Based Stabilization of Expansive Clay Soils: Effects on Swelling, Strength, and Geotechnical Performance

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Abstract- ***Expansive clay soils swell when wet and shrink when dry, which damages pavements and light structures. Biopolymers have been proposed as lower-carbon alternatives to lime and cement, but laboratory results vary. I conducted a systematic review and meta-analysis of open-access laboratory studies, published by 30 April 2025, comparing biopolymer-treated with untreated expansive soils. OpenAlex returned 1,185 records within this date limit, of which 1,178 were unique. Fifty reports were sought; 12 open-access reports could be assessed, and eight studies were included. Effects were expressed as log response ratios, which compare treated with untreated values on a proportional scale. Because almost no study reported variability, study-level ratios were pooled without precision weighting and are presented with t-based 95% confidence intervals. Mean estimates favored treatment for swell (k = 6; -43.8%, 95% CI -72.8% to +16.4%), unconfined compressive strength (k = 4; +117.2%, 95% CI -15.3% to +456.6%), and plasticity index (k = 4; -59.2%, 95% CI -88.0% to +38.8%), but every confidence interval included no change. One study reported more swell after xanthan and guar treatment at 0.5%. The available evidence suggests possible average improvements but does not establish them. The certainty of these estimates is limited by few studies, unreported replication, restriction to open-access reports, single-reviewer screening, and a lack of field data.***

Index Terms- ***biopolymer, expansive soil, meta-analysis, soil stabilization, swelling, unconfined compressive strength***

I. INTRODUCTION

Expansive clays change volume as their water content changes, and this behavior creates persistent problems for pavements and lightly loaded structures (Petry & Little, 2002). Engineers commonly treat these soils with chemical additives, and the range of available stabilizers has been reviewed in detail (Barman & Dash, 2022; Ikeagwuani & Nwonu, 2019). Traditional calcium-based treatment has known limitations. In soils containing sulfates, for example, lime reactions have been linked to heave (Mitchell & Dermatas, 1992). Cement production is also a substantial global source of carbon dioxide (Andrew, 2018). These concerns have increased interest in biopolymers, which have been presented as environmentally friendly alternatives to traditional stabilizers (Kareem & Fadhil, 2024; Khajeh et al., 2024). Xanthan gum, a polysaccharide of microbial origin (Gupta & Kumar, 2024), has been studied as a soil-strengthening additive (Chang et al., 2015).

Reviews have covered biopolymer additives for expansive soils (Kareem & Fadhil, 2024) and lignosulfonate as a soil stabilizer (Khajeh et al., 2024). A quantitative summary would help engineers judge how large and how consistent the reported effects are. My search did not identify a meta-analysis limited to expansive soils. This review therefore asked three questions: (a) how biopolymer treatment is associated with swelling; (b) how it is associated with strength; and (c) how it is associated with plasticity and other geotechnical properties, when each is compared with untreated soil.

II. METHODS

A. Reporting and protocol

The review was reported with reference to PRISMA 2020 (Page et al., 2021).

B. Information source and search

I searched OpenAlex, an open index of scholarly works (Priem et al., 2022), on 9 November 2026 and limited inclusion to records with a publication date of 30 April 2025 or earlier. Title and abstract searches paired one biopolymer block with each soil block below. No language limits were applied, and articles, reviews, preprints, dissertations, and book chapters were eligible for retrieval.

Block	Search terms
Biopolymer (Q1 to Q5)	biopolymer, bio-polymer, xanthan, guar, gellan gum, chitosan, sodium alginate, alginate, beta-glucan, agar, carrageenan, lignosulfonate, lignin, starch, casein, polysaccharide
Q1	expansive AND (soil OR clay)
Q2	swelling AND (soil OR clay)
Q3	bentonite AND (swell OR swelling) AND (stabilization OR stabilisation OR strength)
Q4	black cotton soil
Q5	high plasticity clay, highly plastic clay, or montmorillonite clay soil
Q6 (standalone)	biopolymer AND (stabilization OR stabilisation OR treated OR treatment) AND clay AND (swell OR swelling OR unconfined compressive strength)

C. Eligibility

Studies were eligible if they met all of the following criteria: (a) the soil was described as expansive, swelling, or black cotton, or was high-plasticity clay with evidence of swelling, and reported index values did not contradict that description; (b) a natural biopolymer or lignin-derived biopolymer was applied without another binder in at least one treatment arm; (c) an untreated control was reported or could be derived from a reported percentage change; (d) at least one of swell, swell pressure, unconfined compressive strength (UCS), plasticity index, or California bearing ratio (CBR) was given as a printed number; and (e) the full text was openly accessible and readable. Values available only in figures were not digitized. Values that could not be reconciled within a report were excluded.

D. Selection

Duplicates were removed by DOI and normalized title. A keyword filter then required terms for a biopolymer, a clay, a geotechnical outcome, a treatment, and a soil or engineering context. This filter left 111 records. Another 96 records without abstracts had biopolymer and soil terms in their titles. All 207 were screened by title and abstract. Screening was conducted once with AI assistance, without independent duplicate screening.

E. Data extraction

For each study I recorded soil properties, biopolymer type, dosage, curing, untreated and treated values, replicates, and variability, along with the table or section of origin. Where several curing periods were reported, I used the longest period with a matched control. Where the control was not matched to curing time, the uncured comparison was used for the primary analysis. Full-text values were read through an automated web reader, and every value used in the analysis was checked in a second pass against the source text.

F. Quality appraisal

No validated tool exists for this type of laboratory study, so I used a five-item descriptive checklist: (a) soil characterized; (b) dosage reported; (c) replicates stated; (d) variability reported for the extracted outcome; and (e) no internal inconsistency affecting the study's reporting. Each item scored one point. Scores were used only for sensitivity analysis.

G. Synthesis

The effect measure was the log response ratio, ln(treated value / untreated value). It describes a proportional change and is widely used to summarize experimental comparisons (Hedges et al., 1999; Lajeunesse, 2015). A value of zero indicates no difference. Results were converted back to percentage change for presentation. Multiple dosages or biopolymers within a study share a control, so they were averaged to give one effect per study.

Conventional inverse-variance weighting needs a standard deviation and sample size for each group, which were almost never available. Methods exist for partially missing standard deviations (Nakagawa et al., 2023), but they require some studies to report them. I therefore calculated the unweighted mean of study effects, with a 95% confidence interval based on the t distribution and a 95% prediction interval, which estimates the likely range of effects in a new comparable study. Small-sample bias corrections for response ratios also rely on variability data and were not applied (Lajeunesse, 2015). The I^2 statistic and funnel-plot tests of small-study effects could not be calculated for the same reason. Pooling required at least four studies. Swell pressure and CBR did not reach this threshold and are described narratively. Analyses and figures were produced in R (version 4.3.3) with the ggplot2 package.

Sensitivity analyses (a) replaced the mean dosage with each study's most favorable dosage; (b) restricted to polysaccharides and, where three or more studies allowed, lignin-derived materials; (c) removed estimates derived from percentage changes; (d) restricted to studies scoring at least three; (e) removed one study at a time; and (f) addressed specific data concerns noted in the Results.

III. RESULTS

A. Study selection

The search returned 1,185 records with publication dates by 30 April 2025, and 1,178 remained after duplicates were removed. Of these, 1,128 were excluded at title and abstract screening, and 50 reports were sought. Thirty-eight were not retrieved: 28 had no open-access copy, nine open-access copies could not be read through automated access, and one was a duplicate preprint. Twelve reports were assessed in full, and four were excluded. Eight studies were included (Figure 1).

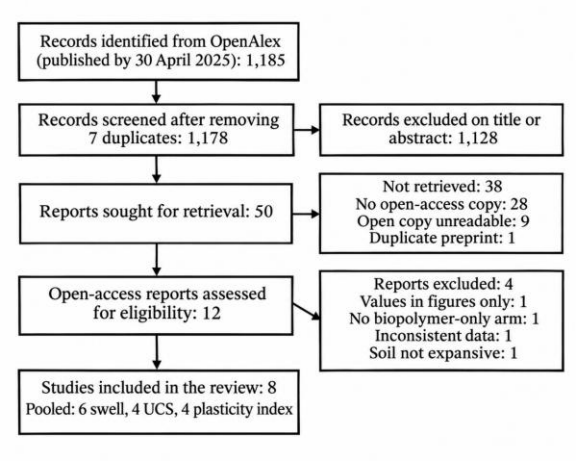


Figure 1. PRISMA 2020 flow diagram of record identification, screening, and inclusion.

Two exclusions need comment. One treated soil was called expansive but had a plasticity index of 4.24, which does not fit that description, even though this was the only report giving complete replicate-level UCS data. Another reported untreated and treated UCS with a stated ratio that did not match its printed values, alongside conflicting index properties.

B. Characteristics of included studies

Studies were published from 2015 to 2025 and were conducted in India, China, Iraq, Iran, and Canada (Table 1). Five examined polysaccharides and three examined lignin-derived materials. All were laboratory studies. One stated the number of replicates for the extracted outcome, and none reported variability for an extracted outcome. Quality scores ranged from two to four of a possible five.

Table 1. Characteristics of included studies

Study	Location	Soil (LL %, PI %)	Biopolymer and dosage	Outcomes	Score
Al-Mousawi & Fadhil (2025)	Baghdad, Iraq	70% clay, 30% bentonite (86.45, 48.51)	Psyllium biogel, 0.4 to 1.6%	Swell, swell pressure, UCS, PI	3
Bukhary & Azam (2024)	Regina, Canada	CH (71, not available)	Chitosan, guar, xanthan, 0.5%	Swell	3
Cai & Ou (2023)	Yunnan, China	Weakly expansive (54.01, 31.43)	Calcium lignosulfonate, 1 to 4%	Swell, PI	3
Gupta & Kumar (2024)	Sonebhadra, India	Expansive black soil (53, not available)	Xanthan gum, 0.2 to 1%	Swell, swell pressure, UCS	2
Lekha et al. (2015)	Karnataka, India	CH (64, 33)	Electrolyte lignin, 1 ml per 3 kg soil	Swell, UCS, PI, CBR	4
Mousavi et al. (2023)	Mazandaran, Iran	CH (64.3, 33.73)	Sodium nanoalginate, 7%	PI	2
Sathyapriya et al. (2023)	Coimbatore, India	CH (51, 24)	Guar gum, 0.5 to 2%	Swell	2
Venu et al. (2024)	West Godavari, India	CH (67, 41.18)	Calcium lignosulfonate, 4%	UCS	3

Note. LL = liquid limit; PI = plasticity index; CH = high-plasticity clay; UCS = unconfined compressive strength; CBR = California bearing ratio. Score refers to the five-item appraisal.

C. Swelling

Across six studies, the mean change in swell was a 43.8% reduction, but the confidence interval included no change (95% CI 72.8% reduction to 16.4% increase; Figure 2). Study effects ranged from an 84.0% reduction (Lekha et al., 2015) to an 18.6% increase (Bukhary & Azam, 2024). In the study reporting an increase, 0.5% chitosan was associated with 11.5% less swell, whereas 0.5% guar gum and 0.5% xanthan gum were associated with 20.5% and 56.4% more swell. The prediction interval ran from a 93.0% reduction to a 349.9% increase.

Dosage patterns differed. In Al-Mousawi and Fadhil (2025), swell fell steadily from 13.5% to 3.23% as psyllium rose from 0% to 1.6%. In Sathyapriya et al. (2023), differential free swell was lowest at 0.5% guar gum (40%, against 60% untreated) and rose slightly at higher dosages.

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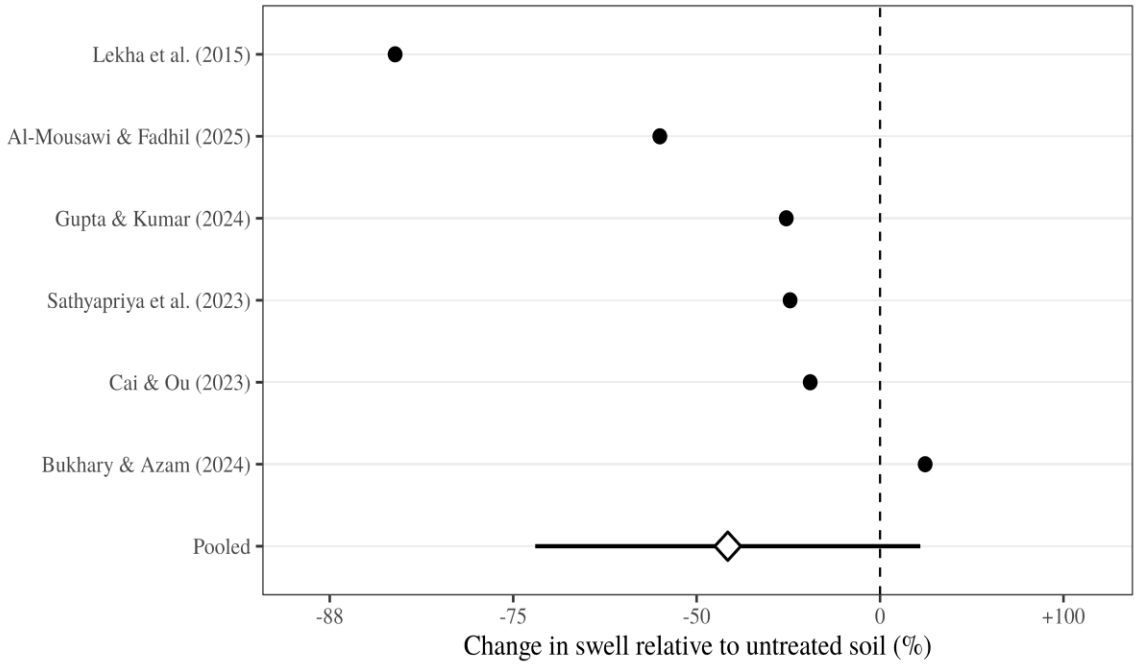


Figure 2. Study-level and pooled percentage change in swell after biopolymer treatment. Filled circles are study means; the open diamond and line are the pooled mean and 95% confidence interval. Study estimates have no individual intervals because variability was not reported. The axis is logarithmic.

D. Unconfined compressive strength

Across four studies, the mean change in UCS was a 117.2% increase, but the confidence interval included no change (95% CI 15.3% decrease to 456.6% increase; Figure 3). Study effects ranged from a 13.9% increase, for uncured specimens (Gupta & Kumar, 2024), to a 320.3% increase (Lekha et al., 2015). The prediction interval ran from an 87.4% decrease to a 3,638.1% increase, which reflects the small number of studies.

One study reported a strength peak followed by a decline, with UCS highest at 0.8% psyllium (Al-Mousawi & Fadhil, 2025). Curing also raised strength in untreated soil. In Al-Mousawi and Fadhil (2025), untreated UCS rose from 204.51 kPa at 0 days to 484.77 kPa at 14 days, and the relative advantage of 0.8% psyllium narrowed from 81.3% to 14.4%.

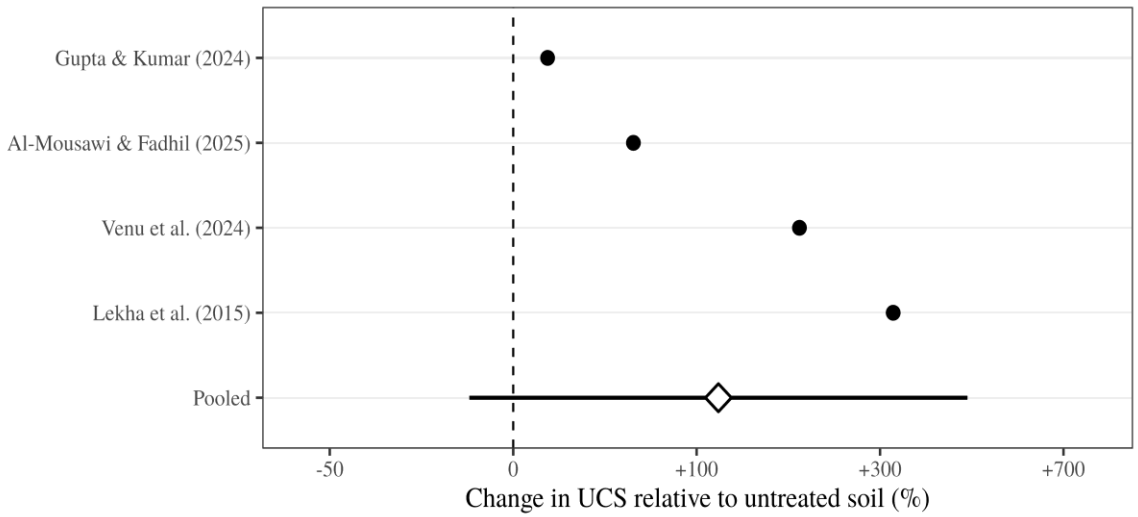


Figure 3. Study-level and pooled percentage change in unconfined compressive strength after biopolymer treatment. Filled circles are study means; the open diamond and line are the pooled mean and 95% confidence interval. The axis is logarithmic.

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E. Plasticity index

Across four studies, the mean change in plasticity index was a 59.2% reduction, but the confidence interval included no change (95% CI 88.0% reduction to 38.8% increase; Figure 4). Study effects ranged from a 12.1% reduction (Al-Mousawi & Fadhil, 2025) to an 83.5% reduction (Cai & Ou, 2023). Most studies printed plasticity index values for only selected dosages, usually the most favorable. The prediction interval ran from a 99.0% reduction to a 1,552.6% increase.

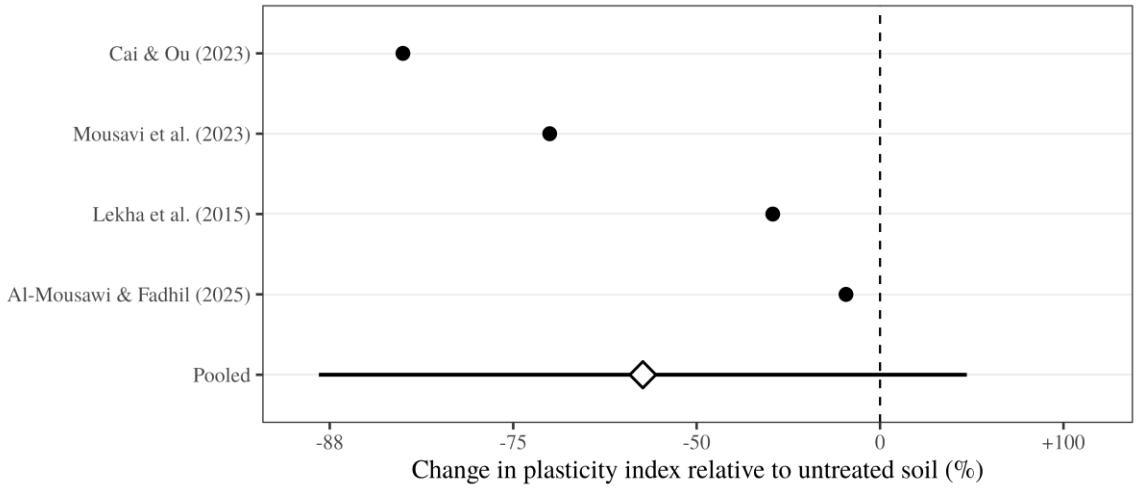


Figure 4. Study-level and pooled percentage change in plasticity index after biopolymer treatment. Filled circles are study means; the open diamond and line are the pooled mean and 95% confidence interval. The axis is logarithmic.

F. Outcomes not pooled

Only one study reported CBR, which rose from 1% to 5% with electrolyte lignin, based on values printed as whole numbers (Lekha et al., 2015). Swell pressure was lower in both reporting studies. It fell by a mean of 54.9% across psyllium dosages (Al-Mousawi & Fadhil, 2025) and by 54.05% with 1% xanthan gum after seven days (Gupta & Kumar, 2024).

G. Sensitivity analyses

The direction of each pooled estimate did not change (Table 2). Removing one study at a time gave swell reductions of 27.7% to 51.5%, UCS increases of 74.2% to 169.3%, and plasticity index reductions of 44.8% to 68.4%. Confidence intervals included no change in every analysis except the one using 28-day values for Gupta and Kumar (2024), where UCS rose by 140.4% (95% CI 14.7% to 403.8%). Analyses of polysaccharides or lignin-derived materials alone were mostly not possible because fewer than three studies were available.

Table 2. Sensitivity analyses: mean percentage change from untreated soil (95% CI)

Analysis	Swell	UCS	Plasticity index
Primary	-43.8 (-72.8, +16.4); k = 6	+117.2 (-15.3, +456.6); k = 4	-59.2 (-88.0, +38.8); k = 4
Most favorable dosage	-52.0 (-77.3, +1.3); k = 6	+127.4 (-5.6, +448.0); k = 4	-59.2 (-88.0, +38.8); k = 4
Polysaccharides only	-28.8 (-62.9, +36.7); k = 4	Too few studies	Too few studies
Lignin-derived only	Too few studies	Too few studies	Too few studies
No percent-derived estimates	-46.2 (-79.2, +39.3); k = 5	No such estimates	No such estimates
Quality score of 3 or more	-49.8 (-87.3, +98.9); k = 4	+169.3 (-21.7, +825.9); k = 3	-54.1 (-95.1, +326.5); k = 3
Excluding swell value with inferred table layout	-27.7 (-53.5, +12.6); k = 5	Not applicable	Not applicable
Excluding control not matched to curing	Not applicable	+96.1 (-63.8, +961.8); k = 3	Not applicable
Gupta & Kumar at 28-day curing	Not applicable	+140.4 (+14.7, +403.8); k = 4	Not applicable

Note. k = number of studies.

IV. DISCUSSION

In this set of open-access laboratory studies published by April 2025, average estimates favored biopolymer treatment for swell, compressive strength, and plasticity. None of the primary confidence intervals excluded no change, so the data do not establish an average benefit. With so few studies, the intervals are wide, and pooled values should not be

read as the performance to expect at a particular site. The strongest caution concerns swelling. It is the defining problem of these soils, yet the pooled interval for polysaccharides ranged from a sizable reduction to an increase. Bukhary and Azam (2024) reported more swell with guar and xanthan gum, while other studies of these materials reported less (Sathyapriya et al., 2023; Gupta & Kumar, 2024). This review cannot explain the difference. Soil type, dosage, specimen preparation, swell test type, and curing varied together across a small number of studies.

The strength results also suggest that more biopolymer is not always better, since one study reported a decline after a peak dosage (Al-Mousawi & Fadhil, 2025). Curing deserves attention as well. The narrowing advantage in Al-Mousawi and Fadhil (2025) shows that comparing cured treated specimens with uncured controls can overstate a benefit. The 13.9% uncured and 71.1% 28-day UCS estimates for Gupta and Kumar (2024) illustrate how much this choice can matter, because the same control value was printed for all curing periods.

The broader appeal of biopolymers rests partly on the limitations of cement and lime (Andrew, 2018; Mitchell & Dermatas, 1992). None of the pooled comparisons tested a biopolymer against those binders, so this review does not show that biopolymers perform equally well. The pooled set also combined polysaccharides with lignin-derived materials, so a single figure for all biopolymers has limited practical meaning.

A. Limitations

The review has important limitations. (a) Restricting analysis to open-access papers excluded 28 potentially eligible paywalled reports, and open-access status may be related to journal type and results. (b) Nine open-access reports could not be read through automated access, and several of these are likely eligible. (c) Screening and extraction were not independently duplicated. (d) Data were extracted from text and tables only, so studies presenting results in figures were lost, and selective reporting of favorable dosages likely affected plasticity index in particular. (e) Almost no study reported variability, so studies could not be weighted by precision, heterogeneity statistics could not be calculated, and publication bias could not be formally tested. (f) Averaging dosages within studies combines effective and ineffective amounts, although the most favorable dosage analysis gave estimates in the same direction. (g) Swell measurements included free swell index, differential free swell, and oedometer swell, which are not interchangeable even on a proportional scale. (h) Several included reports contained internal inconsistencies, and some came from journals with limited reporting detail. (i) No protocol was registered. (j) OpenAlex was the only database searched, and coverage may differ from other indexes (Culbert et al., 2025). (k) All evidence is from laboratory specimens, so durability, biodegradation, and field performance remain unaddressed here. (l) Studies published after 30 April 2025 were excluded, and the number of studies per outcome was small.

B. Implications for research

Future laboratory studies would be far more useful for synthesis if they (a) reported the number of replicates with a mean and standard deviation for each dosage; (b) tabulated values rather than presenting them only in figures; (c) tested untreated controls at every curing period; (d) included a lime or cement comparison; and (e) reported wet-dry durability and longer-term performance.

V. CONCLUSIONS

Open-access laboratory evidence published by April 2025 gives average estimates favoring biopolymer treatment of expansive clay soils for swell, unconfined compressive strength, and plasticity index, but the confidence intervals all included no change. Results varied considerably between studies and included cases of increased swell. Current evidence supports continued investigation and does not establish reliable design values. Larger syntheses that include paywalled studies, and primary studies that report variability and matched controls, are needed.

DECLARATIONS

Funding: No funding

Competing interests: No

Data availability: The search strategy is reported in this article. The extracted effect sizes with source locations and the R analysis code are available as supplementary files.

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