7th Conference on Sustainability in Civil Engineering (CSCE'25)
(An International Conference)
Department of Civil Engineering
Capital University of Science and Technology, Islamabad Pakistan

MECHANICAL AND MICROSTRUCTURAL ENHANCEMENT OF EXPANSIVE SOILS VIA SUSTAINABLE WASTE GLASS POWDER AND FLY ASH BLENDS

[a] Muhammad Usama*, [b] Ubaid Ullah, [c] Muhammad Rauf

a: Department of Geodesy and Geoinformatics, Hamburg, Germany. ukhattak999@gmail.com
b: Department of civil Engineering, University of Wah, Wah Cantt, 47040, Pakistan. ubaidkhattak999@gmail.com
c: Department of civil Engineering, University of Wah, Wah Cantt, 47040, Pakistan.engr.roufktk@gmail.com
*Corresponding Author

Abstract- Expansive soils, particularly high-plasticity clays, pose significant challenges for construction due to their low shear strength, poor compaction, and shrink-swell behavior. `. Conventional stabilizing methods, such as those using lime or cement, are often associated with high costs and significant environmental impacts. This study investigates the use of two industrial byproducts, waste glass powder (WGP) and fly ash (FA),as sustainable stabilizers for expansive soils. Laboratory tests were conducted using varying contents of WGP (5–30%) and FA (5–17%) to assess improvements in compaction, strength, plasticity, and swell potential. The optimal blend of 25% WGP and 11% FA yielded significant enhancements: UCS increased by 178% to 401.29 kPa, plasticity index reduced by 69% to 11.13%, swell potential dropped by 76% to 6%, and dry density increased to 1.92 g/cm³. Shear strength improvements were also observed, with the angle of internal friction rising by 103% to 35.94° and cohesion reduced to 9 kPa. SEM and XRD analyses confirmed the formation of dense cementitious compounds, validating the microstructural improvement. These findings indicate that WGP and FA provide a sustainable and cost-effective alternative for stabilizing expansive soils in civil engineering applications.

Keywords- Soil stabilization, Waste Glass Powder, Fly Ash, Expansive soils, High-Plasticity Clays, Sustainability

and cost-effective solutions for such a worst soil . The conventional techniques of soil stabilization may include the utilization of cement, lime, etc., which may cause environmental degradation [7][8].

WGP and FA's cooperative action on soil stability has attracted interest in its combined application .Combining the two pozzolanic materials with the clay minerals in expansive soils results in cementitious compounds that lower swelling potential and fluidity and boost strength. Combining WGP with FA significantly reduces the swell potential of expansive soils while concurrently boosting the UCS and shear strength, claims research by Hawkar et al. and Ibrahim et al [9] [10]. While the appropriate ratio depends on the kind of soil and environmental conditions, WGP content up to 25% and FA content up to 20% generally show the best results in terms of strength increase and expansibility reduction.

Techniques like scanning the microstructural alterations has been made easier by X-ray diffraction (XRD) and scanning electron microscopy (SEM) in soils treated with WGP and FA [11], [12] .XRD investigations indicate that pozzolanic compounds such C-S-H are produced when WGP reacts with clay minerals, therefore reducing soil expansivity and increasing soil strength [13]. Further verifying the densification of soil samples after treatment are SEM images, which show a more coherent and stable microstructure. These microstructure changes produce better compaction and lower porosity, two improved mechanical properties of the stabilized soils that come from which soil stability is raised [14], [15].

Local stakeholders' settlement issues led to the sample for this study being taken from an Islamabad, Pakistan's developing sector B-17 site. The soil was investigated (of site as shown in Figure 1 in the lab in order to assess certain properties. Tests conducted on both untreated and treated samples included swell potential, Compaction characteristics; unconfined compressive strength; direct shear testing; The limits of Atterberg (also known as the plastic limit (PL), liquid limit (LL), and index of plasticity (PI). The soil and additives (fly ash and waste glass powder) were also subjected to X-ray diffraction (XRD) and SEM (scanning electron microscopy) was employed to evaluate the microscopic characteristics of the two treated and untreated specimens. The initiative aims to maximize fly ash and residual glass powder use in order to improve soil properties.

Figure 1:(a,b) Jacks are used to prevent settling in both freshly built and older homes, as well as fissures caused by expansive soils' volume change behaviour .

2 Research Methodology

2.1 Materials

The high-plasticity clay (CH classification) was sourced from Islamabad, Pakistan, exhibiting a liquid limit of 51.36% and plasticity index of 26.36%. Waste glass powder (WGP) was obtained from Gunj Glassworks (63.99% SiO_2, angular particles), while fly ash (FA) was procured from Fecto Cement Factory (37.81% SiO_2, spherical particles).Figure 2 shows the physical samples of soil, WGP, and FA. Key properties of untreated soil are summarized in Table 1.

Figure 2:Samples of Fly Ash, WGP, and Soil

2.2 Methodology

The experimental program comprised three phases. Phase I involved characterizing untreated soil and additives through sieve analysis, Atterberg limits, compaction tests, UCS, and shear testing (Figure 5a–c). Phase II optimized WGP content (5–30%), while Phase III evaluated synergistic effects by blending optimal WGP (25%) with varying FA (5–17%). Advanced microstructural analysis using XRD, and SEM elucidated stabilization mechanisms. Sieve analysis per ASTM D6913 confirmed the untreated soil's composition (73% clay, 17.8% silt, 9.2% sand), while WGP (90% <0.075 mm) and FA (85% <0.045 mm) exhibited finer gradations, enabling optimal void filling and pozzolanic reactivity for soil stabilization.

3 Results and Discussion

3.1 Phase I: Soil and Additive Characterization

Phase I characterization of untreated soil revealed a high-plasticity clay (CH classification) with liquid limit=51.36%, plasticity index=26.36%, free swell index=25.5%, and specific gravity=2.73; compaction tests showed maximum dry density=1.60 g/cm³ at 19.64% optimum moisture content, while unconfined compressive strength increased from 77.42 kPa (1 day) to 144.25 kPa (28 days), and direct shear testing measured cohesion=22.14 kPa with friction angle=17.74° as shown in Table 1. These results demonstrate the soil's highly expansive nature, low inherent strength, and poor engineering properties – confirming significant susceptibility to moisture-induced volume changes, structural settlement, and shear failure, which necessitates stabilization for construction applications.

3.2 Phase II. Optimization of Waste Glass Powder (WGP)

In Phase II, the soil is treated with Waste Glass Powder (WGP) by varying its percentages to optimize the treatment. The percentages used for WGP were 5%, 10%, 15%, 20%, 25%, and 30%. The effects of these varying percentages were assessed using several tests to determine the optimal level of WGP for improving soil properties as shown in Table 2 .plasticity index decreased by 51% (to 12.81%), maximum dry density increased by 15% (to 1.84 g/cm³), unconfined compressive strength (UCS) surged 166% (to 383.7 kPa at 28 days), and friction angle improved to 26.34°—though cohesion decreased by 33% (to 14.77 kPa) due to WGP's non-cohesive nature; however, exceeding 25% (up to 30% WGP) caused UCS to decline by 23% (to 294.28 kPa) and maximum dry density to reduce to 1.80 g/cm³, while swell potential reduction plateaued and friction angle marginally increased to 27.02°, indicating diminished returns due to insufficient pozzolanic binder-clay interaction and disrupted moisture distribution from excessive granular filler. This threshold behaviour confirms WGP's dual role: optimal at 25% for densification and strength gain through void-filling and pozzolanic reactions, but counterproductive beyond due to particle segregation, reduced cohesion, and inhibited cementitious gel formation.

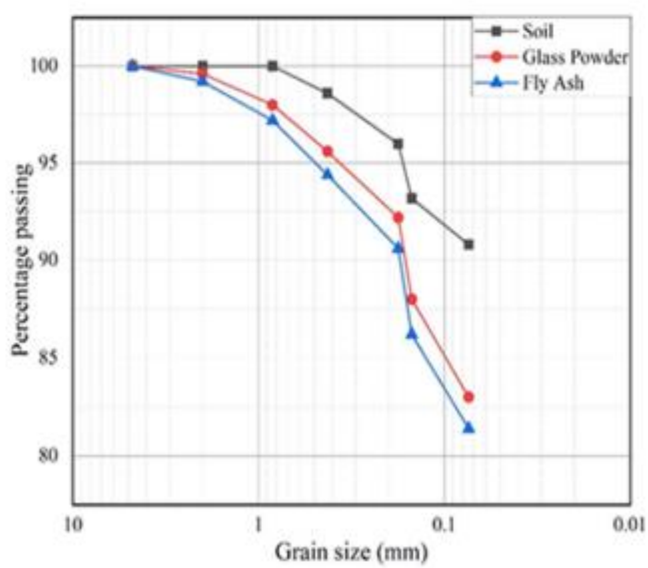


Figure 3:Grain size distribution of untreated soil, WGP, and FA

Table 1:Expanding soil characteristics and the corresponding ASTM standards

Properties of Expansive Soil	Values	Standards
Sieve Analysis	90.80%(Totally Fine i.e silt + clay)	ASTM D7928
Specific gravity of soil	2.74	ASTM D854
Liquid limit	51.36%	ASTM D4318
Plastic Limit	25%	ASTM D4318
Plasticity Index	26.36%	ASTM D4318
Sand	9.20%	ASTM D6913
Silt	17.80%	ASTM D6913
Clay	73%	ASTM D6913
Modified Free swell Index	25.5%,	ASTM D5890-19
USCS Classification	CH	ASTM D2487
Maximum Dry Density	1.60 g/cc	ASTM D698
Optimum Moisture Content	19.64%	ASTM D698
UCS1d (untreated)	77.42 kPa	ASTM D2166
UCS3d	92.8 kPa	ASTM D2166
UCS7d	102.94 kPa	ASTM D2166
UCS14d	132.27 kPa	ASTM D2166
UCS28d	144.25 kPa	ASTM D2166
Cohesion	22.14 kPa	ASTM D2166
Angle of Internal Friction	17.74°	ASTM D6528

Table 2:Summary of phase II Optimization of WGP

Percentage of WGP	Unit	5%	10%	15%	20%	25%	30%
Specific Gravity		2.36	2.32	2.26	2.25	2.23	2.18
Swell Potential		21	19	17	16	14	13
LL(%)	(%)	44.8	40.76	37.23	33.17	27.31	20.145
PL(%)	(%)	22	18	17	16	15	10
PI(%)	(%)	22.8	22.26	22.23	17.17	12.81	9.64
OMC(%)	(%)	19.5	18.6	17	15.66	13	11.6
MDD(%)	(%)	1.71	1.73	1.78	1.79	1.84	1.8
UCS 1st day	(kPa)	87.05	98.67	106.3	112.36	117.6503	108.69
UCS 3rd day	(kPa)	100.74	138.76	156.4	163.65	170.9125	161.26
UCS 7th day	(kPa)	108.28	147.13	167	180.7	190.3344	168.53
UCS 14th day	(kPa)	144.65	148.93	190.9	233.07	287.6731	245.04
UCS 28th day	(kPa)	283.26	328.8	341	360.58	383.7021	294.28
Cohesion	(kPa)	22.93	20	19.1	17.83	14.77	10.91
Angle of Internal Friction	(Degree)	19.29	21.32	23.26	26.01	26.34	27.02

3.3 Phase III

Combining the optimal 25% waste glass powder (WGP) with fly ash (FA) further enhanced soil stabilization, peaking at **11% FA as shown in** Table 3: unconfined compressive strength (UCS) reached 401.29 kPa (178% higher than untreated soil), maximum dry density increased to 1.92 g/cm³, and swell potential dropped to a minimal 6%. Plasticity index reduced to 11.13%, while shear strength shifted toward frictional resistance (friction angle: 35.94°) with reduced cohesion (9 kPa). Beyond 11% FA (e.g., 17% FA), UCS declined by 16% (to 336.72 kPa), density decreased slightly (1.89 g/cm³), and cohesion further diminished (8 kPa), though friction angle rose to 41°. This synergy stems from FA's ultra-fine particles (<0.045 mm) filling micropores and amplifying pozzolanic reactions with WGP's silica, forming dense calcium silicate hydrate gels that strengthen the soil matrix—but excessive FA dilutes reactive surfaces, weakening binding efficiency. The 25% WGP + 11% FA blend thus represents the ideal equilibrium for maximizing strength, density, and swell control.Hence, with 25% WGP + 11% FA, the soil transitions from CH (high-plasticity clay) to CL (low-plasticity clay) per ASTM D2487, with LL=24.3% (<50%) and PI=11.13% (above A-line: PI=0.73×(LL-20)=3.14%). This confirms the reduction in expansivity and validates the efficacy of stabilization using a standardized classification

3.4 XRD Analysis of Clay, Waste Glass Powder, and Fly Ash

X-ray diffraction (XRD) analysis elucidated the mineralogical foundations of stabilization efficacy, revealing that the untreated expansive soil contained quartz, kaolinite, illite, and highly expansive montmorillonite as show in Figure 4,the latter explaining its pronounced shrink-swell behaviour. Waste glass powder (WGP) exhibited a dominant quartz crystalline structure, while fly ash (FA) featured complex crystalline phases including mullite, hematite, goethite, anorthite, and magnesium hydroxide. Critically, after blending 25% WGP and 11% FA with the soil, XRD detected calcium silicate hydrate (C-S-H) formation—a key pozzolanic reaction product alongside reduced montmorillonite peak intensity.

Table 3:Summary of Phase III: Synergistic Effect of WGP and Fly Ash (FA)

FA WGP	Unit	5% 25%	8% 25%	11% 25%	14% 25%	17% 25%
Specific Gravity		2.33	2.28	2.22	2.2	2
Free Swell Index		18	15	13	9	6
LL	(%)	26.46	25.04	24.3	22.46	19.56
PL(%)	(%)	14.67	13.7	13.17	11.5	9.83
PI(%)	(%)	11.79	11.34	11.13	10.96	9.73
OMC(%)	(%)	13.33	12.66	11.66	11	10.33
MDD(%)	(%)	1.86	1.88	1.92	1.91	1.89
UCS (kPa) 1st day	(kPa)	117.33	142.43	166.97	154.38	125.49
UCS (kPa) 3rd day	(kPa)	161.26	192.73	218.92	199.73	178.68
UCS (kPa) 7th day	(kPa)	198.37	232.32	272.97	225.29	190.33
UCS (kPa) 14th day	(kPa)	229.63	285.38	329.22	291.34	265.5
UCS (kPa) 28 day	(kPa)	232.12	310.45	401.29	366.35	336.72
Cohesion(kpa)	(kPa)	12.48	9.42	9	8.7	8
Angle of Internal Friction	(Degree)	32.3	34.13	35.94	37	41

This mineralogical evolution confirms WGP's quartz-enhanced particle interlocking and shear resistance, while FA's mullite and hematite reinforced mechanical strength, collectively transforming the soil into a stabilized matrix with diminished expansivity and heightened durability.

3.5 The Effect of Clay Content, FA, and WGP on Microstructural Behaviour (SEM)

Scanning electron microscopy (SEM) revealed transformative microstructural changes induced by WGP and FA treatment. Untreated soil exhibited a loose, porous matrix with visible voids and minimal particle bonding (Figure 5a), explaining its low strength and high swell potential. With 25% WGP addition (Figure 5b), pozzolanic reactions generated dense, gel-like structures that entrapped glass particles, reducing porosity and forming incipient cementitious bonds. The synergistic 25% WGP + 11% FA blend (Figure 5c–d) produced a radically densified microstructure where fly ash's spherical particles embedded uniformly within cementitious gels, transforming flaky clay into cohesive, blocky aggregates. Notably, FA's spherical morphology complemented WGP's angular particles, enhancing interlocking and creating a continuous binding framework that minimized voids. This microstructural evolution directly correlated with macro-scale improvements: the homogeneous, cemented matrix increased unconfined compressive strength by 178% and reduced swell potential by 76%, confirming that WGP-FA synergy effectively restructures expansive clays into stable, load-bearing materials.Both WGP and FA are pozzolanic materials, meaning they contain high amounts of amorphous silica (SiO_2) and alumina (Al_2O_3). While they are not cementitious on their own, they react chemically with calcium hydroxide ($Ca(OH)_2$)—either naturally present in clay or added externally (from lime or portlandite in soil minerals)—in the presence of moisture to form cementitious compounds.

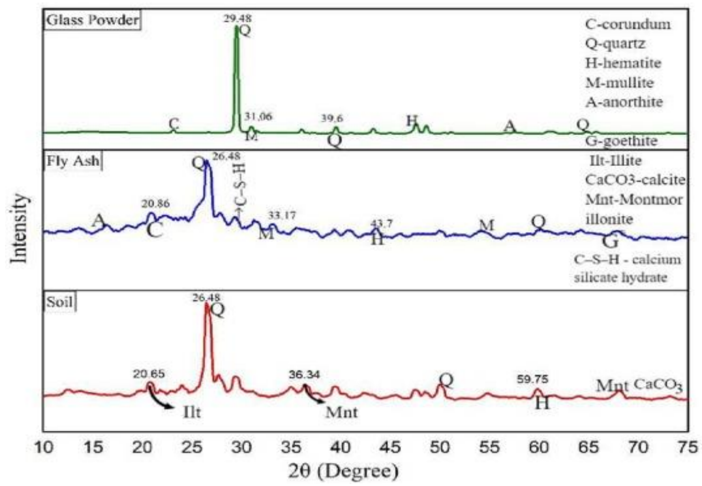
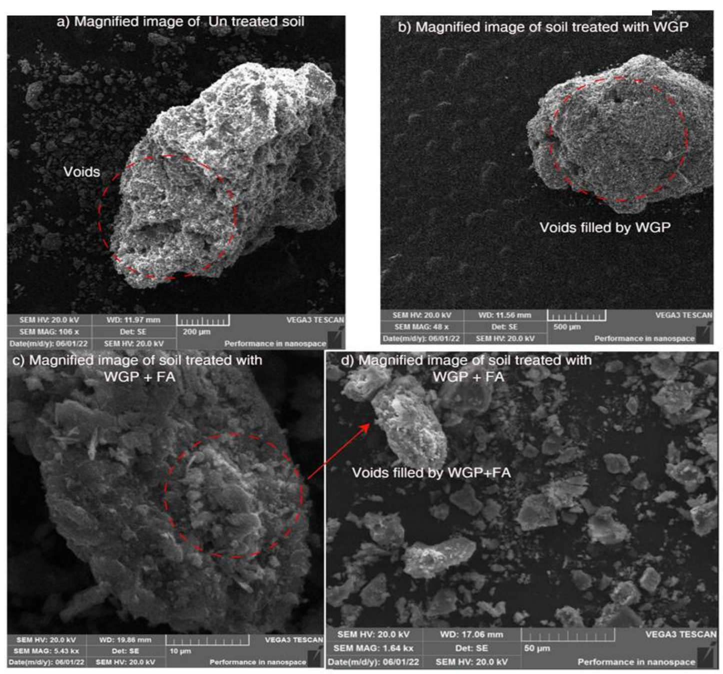


Figure 4:XRD of Clay, WGP, and FA



.

Figure 5:Untreated expansive soil (a), WGP-treated soil (b), and WGP and FA-treated soil (c,d) were all subjected to SEM examination.

4 Practical Implementation

This stabilization method can be effectively applied in road construction and foundation work by blending 25% waste glass powder (WGP) and 11% fly ash (FA) with expansive soils. Using standard mixing equipment and compacting the mixture at approximately 11.7% moisture content achieves the target dry density of 1.92 g/cm³. The materials, sourced from local glass recycling facilities and power plants, reduce material costs by 30–40% compared to traditional cement stabilization, while diverting over 36 tons of waste per kilometer of road. Field validation conducted in Pakistan's Potohar region demonstrated a 35% cost reduction and eliminated seasonal maintenance caused by swelling-related cracking, confirming the method's viability for infrastructure projects in expansive clay regions. For shallow, high-plasticity soil layers (less than 1 meter), soil removal or basement construction may be more cost-effective than stabilization. However, for deeper deposits, such as at the B-17 site, with an expansive layer depth of 2.5 meters, stabilization using 25% WGP and 11% FA reduces costs by 35–40% compared to cement-based methods and eliminates the need for long-term maintenance. A preliminary cost-benefit analysis further confirmed savings of approximately 30% compared to removal and replacement strategies for road sections with expansive strata exceeding 1 meter in depth.

Conclusion

- The optimal mix of 25% Waste Glass Powder (WGP) and 11% Fly Ash (FA) increased Unconfined Compressive Strength (UCS) by 178%, reaching 401.29 kPa, and reduced swell potential by 76%, down to 6%.
- The Plasticity Index was reduced by 69%, from 26.36% to 11.13%, improving soil workability and reducing volumetric instability.
- The maximum dry density improved from 1.60 g/cm³ to 1.92 g/cm³, while optimum moisture content decreased from 19.64% to 11.66%, enhancing compaction efficiency.
- Shear strength behavior shifted from cohesive to frictional dominance, with the angle of internal friction increasing from 17.74° to 35.94°, and cohesion decreasing to 9 kPa.
- Microstructural (SEM/XRD) analysis confirmed the formation of dense C-S-H gels, validating the strength and stability improvements achieved through the WGP–FA stabilization.

References

[1] D. Barman and S. K. Dash, "Stabilization of expansive soils using chemical additives: A review," *J. Rock Mech. Geotech. Eng.*, vol. 14, no. 4, pp. 1319–1342, 2022.

[2] A. H. Alsabhan and W. Hamid, "Innovative thermal stabilization methods for expansive soils: mechanisms, applications, and sustainable solutions," *Processes*, vol. 13, no. 3, p. 775, 2025.

[3] S. J. Abbey, E. U. Eyo, and S. Ng'ambi, "Swell and microstructural characteristics of high-plasticity clay blended with cement," *Bull. Eng. Geol. Environ.*, vol. 79, no. 4, pp. 2119–2130, 2020.

[4] M. Usama *et al.*, "Predictive modelling of compression strength of waste GP/FA blended expansive soils using multi-expression programming," *Constr. Build. Mater.*, vol. 392, p. 131956, 2023.

[5] S. Fateh, Y. Mansourkiaei, M. M. Shalchian, M. Arabani, M. Payan, and P. Z. Ranjbar, "A comparison of temperature and freeze-thaw effects on high-swelling and low-swelling soils stabilized with xanthan gum," *Results Eng.*, vol. 25, p. 103719, 2025.

[6] H. R. Manaviparast, N. Cristelo, E. Pereira, and T. Miranda, "A Comprehensive Review on Clay Soil Stabilization Using Rice Husk Ash and Lime Sludge.," *Appl. Sci.*, vol. 15, no. 5, 2025.

[7] H. Afrin, "A review on different types soil stabilization techniques," *Int. J. Transp. Eng. Technol.*, vol. 3, no. 2, pp. 19–24, 2017.

[8] H. Gardezi *et al.*, "Predictive modeling of rutting depth in modified asphalt mixes using gene-expression programming (GEP): A sustainable use of RAP, fly ash, and plastic waste," *Constr. Build. Mater.*, vol. 443, p. 137809, 2024.

[9] H. Ibrahim and C. Q. Hassan, "Post-traumatic stress disorder symptoms resulting from torture and other traumatic events among Syrian Kurdish refugees in Kurdistan Region, Iraq," *Front. Psychol.*, vol. 8, p. 241, 2017.

[10] S. Narendra and V. Vasugi, "Development of sintered artificial coarse aggregate by employing the Taguchi optimization technique," *Case Stud. Constr. Mater.*, p. e04724, 2025.

[11] Y. Ordoñez Muñoz, A. J. E. Villota-Mora, F. Perretto, and R. L. dos Santos Izzo, "Eco-friendly stabilization of clayey soil with waste glass powder-based geopolymer," *Geomech. Geoengin.*, vol. 20, no. 3, pp. 557–586, 2025.

[12] A. Minhajuddin and A. Saha, "Performance evaluation of geopolymer concrete with waste granite powder as a sustainable alternative to sand," *J. Mater. Sci. Mater. Eng.*, vol. 20, no. 1, p. 20, 2025.

[13] A. U. Ndaiji, M. Abdullahi, B. A. Abbas, and M. Abubakar, "EFFECTS OF WASTE GLASS POWDER AND CASSAVA PEEL ASH ON COMPRESSIVE STRENGTH OF CONCRETE," Proceeding of the 3rd International Civil Engineering Conference (ICEC 2024), 2025.

[14] Y. Hong, X. Xu, C. Zhang, Z. Cheng, and G. Yang, "Microscopic Mechanism and Reagent Activation of Waste Glass Powder for Solidifying Soil," *Buildings*, vol. 14, no. 5, p. 1443, 2024.

[15] P. Manikandan, V. P. Kumar, and V. Vasugi, "Strength and microstructural characteristics of sustainable aluminosilicate binder using waste glass powder and ground granulated blast furnace slag," *Innov. Infrastruct. Solut.*, vol. 10, no. 3, p. 105, 2025.