

Beyond licensing: pathways to environmental compliance and livelihood stability in formalised artisanal and small-scale mining

Environmental
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Abstract

Purpose – This study explains when formalised artisanal and small-scale mining (ASM) delivers joint environmental compliance and livelihood stability in Nigeria, treating formalisation as a conjunctural bundle of enabling conditions rather than a single net-effect intervention.

Design/methodology/approach – Using a multi-respondent, six-state survey of 212 formalised ASM sites integrating operator, community and regulator assessments, this study validates a multi-attribute Formalisation Quality construct and applies a measurement-then-configuration design. Fuzzy sets are calibrated for formalisation quality, institutional support and trust, mechanisation and clean-technology adoption, community embeddedness and legitimacy, and gender inclusion. Fuzzy-set qualitative comparative analysis (fsQCA) is employed to identify sufficient configurations for high environmental and socioeconomic performance and for their negations.

Findings – Results show equifinality and causal asymmetry. High environmental performance arises via (1) a governance-technology pathway, combining formalisation quality, trusted institutional support and cleaner technology adoption, and (2) a governance-community-inclusion pathway, combining trusted institutions, community embeddedness and gender inclusion, even under moderate mechanisation. High socioeconomic performance arises via (1) a market-community-inclusion pathway, combining formalisation quality, embedded local relations and women's participation, and (2) a state-service technology pathway, combining institutional support and mechanisation. Underperformance follows non-mirror causal structures: weak institutional support and low cleaner-practice capability are associated with environmental underperformance, while weak community embeddedness and limited gender inclusion are associated with livelihood underperformance.

Research limitations/implications – The cross-sectional design constrains temporal inference on sequencing and path dependence; longitudinal renewal-cycle and inspection-history designs are recommended. Future research should combine panel calibration, traceability records, transaction data and more fine-grained gender-inclusion measures, including pay equity, task segmentation, leadership authority and gender-based safety exposure.

Practical implications – Formalisation programmes should be designed and monitored as assemblable “recipes” that combine governance credibility with either capability-upgrading or legitimacy-and-inclusion mechanisms, supported by a replicable audit framework. Rather than treating licences as sufficient policy instruments, regulators and development agencies should diagnose which complementary conditions are absent at the site level and assemble intervention bundles accordingly.

Originality/value – This study advances ASM formalisation theory by specifying testable configurational pathways, repositioning gender inclusion as an enabling condition, and demonstrating a replicable measurement-then-fsQCA workflow for resource-intensive governance contexts. It also integrates political ecology and



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sustainability-transition reasoning by showing that ASM performance depends on how authority, capability, cleaner technology, community legitimacy and inclusion are assembled at the mine-community interface.

Keywords Artisanal and small-scale mining (ASM), Formalisation quality, Sustainability performance, Fuzzy-set qualitative comparative analysis (fsQCA), Institutional support, Community embeddedness, Gender inclusion, Sustainability transitions

Paper type Research article

Introduction

Across mineral-rich regions, artisanal and small-scale mining (ASM) formalisation is advanced as a policy response to occupational harm, environmental degradation, fiscal leakage, and weak state visibility over mineral value chains, yet empirical assessments of what formalisation delivers remain uneven across countries, commodities, and institutional designs (Hilson and Maconachie, 2017; Hilson, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). In gold-producing contexts, the sustainability stakes are amplified by mercury-based processing and its health and ecological burdens, which formalisation programmes seek to reduce through licensing, oversight, technical support, and technology substitution (Minamata Convention on Mercury, 2013; Prescott *et al.*, 2022; Keane *et al.*, 2023; Kohio *et al.*, 2024). Nigeria illustrates both the urgency and the governance difficulty of this agenda: artisanal gold extraction has been associated with severe toxic exposure episodes in mining communities, while recent policy responses have framed formalisation as a route to safer production, regulated trading, and traceable market participation (Dooyema *et al.*, 2012; Presidential Artisanal Gold Mining Initiative, 2020). However, the Nigerian case also exposes a recurrent weakness in ASM policy: formalisation is often treated as if legal recognition alone can produce environmental compliance and livelihood stability, even though political ecology scholarship shows that mining outcomes are shaped by power relations, territorial authority, distributional conflict, and unequal access to state protection and markets (Bebbington, 2015; Hilson, 2020; Beban and Banks, 2023; Adranyi *et al.*, 2024a, b).

Nigeria's formalisation architecture combines statutory licensing rules, institutional mandates, and targeted initiatives that attempt to reconfigure ASM from informal production toward regulated operations embedded within state systems (Minerals and Mining Act, 2007; Presidential Artisanal Gold Mining Initiative, 2020; Mining Cadastre Office, 2025; NESREA, 2025). The Mining Cadastre Office (MCO) operationalises mineral title administration, while the National Environmental Standards and Regulations Enforcement Agency (NESREA) anchors environmental compliance expectations through federal regulatory instruments that intersect with state-level enforcement capacity (Minerals and Mining Act, 2007; NESREA, 2025). PAGMI links artisanal gold formalisation to market coordination, price discovery, and value-chain governance, thereby positioning formalisation as both a compliance mechanism and an economic development instrument (Presidential Artisanal Gold Mining Initiative, 2020; Reuters, 2024). Yet these institutional arrangements operate within uneven enforcement systems, variable local legitimacy, financing constraints, and contested mine-community relations, which means that formalisation may generate substantive improvement, partial compliance, or symbolic legality depending on the conditions that accompany it (Hilson, 2020; Prescott *et al.*, 2022; Eniowo, 2024; Arthur-Holmes and Ofosu, 2024). Despite this institutional build-out, evidence remains limited on how, and under what combinations of enabling conditions, formalised ASM sites produce joint socio-economic gains and improved environmental performance rather than partial, fragile, or symbolic compliance (Hilson, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024; Donkor *et al.*, 2025).

A principal limitation in extant research is methodological as well as theoretical: much of the literature isolates single drivers, reports net effects, or advances descriptive governance narratives that do not specify the conjunctural conditions required to realise sustainability outcomes after licensing (Hilson, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). This limitation is consequential because formalisation is seldom a unitary treatment; it

is a composite institutional intervention whose effects depend on the co-presence of credible oversight, service support, technology uptake, community acceptance, and inclusive participation (Ragin, 2008; Fiss, 2011; Misangyi *et al.*, 2017; Di Paola *et al.*, 2025). Sustainability-transition theory further sharpens this problem by showing that technical change does not diffuse through policy instruction alone, but through socio-technical alignments among institutions, capabilities, infrastructures, markets, and user practices (Smith *et al.*, 2010; Geels, 2011; Boafo and Arthur-Holmes, 2025). In ASM, therefore, cleaner processing and safer work routines cannot be treated as discrete technological inputs; they are conditioned by regulatory credibility, financing access, local trust, and miners' capacity to maintain new practices under income volatility (Prescott *et al.*, 2022; Eniowo, 2024; Kohio *et al.*, 2024). Set-theoretic approaches, including fuzzy-set qualitative comparative analysis (fsQCA), are therefore suitable where equifinality and causal asymmetry are expected and where policy-relevant insight depends on identifying multiple sufficient recipes rather than an average marginal effect (Ragin, 2008; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Saridakis *et al.*, 2022; Di Paola *et al.*, 2025).

We advance a configurational account of formalised ASM performance by theorising that high sustainability performance at the operation-community interface emerges from specific combinations of five conditions: formalisation quality, institutional support and trust, mechanisation and cleaner technology adoption, community embeddedness and legitimacy, and gender inclusion (Fiss, 2011; Misangyi *et al.*, 2017; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024; Di Paola *et al.*, 2025). We define formalisation quality as miners' perceived alignment among licensing, monitoring, procedural intelligibility, and access to enabling services, given evidence that formalisation frequently falters when legal design and administrative practice diverge at the point of implementation (Hilson, 2020; Eniowo *et al.*, 2022a, b; Kumah, 2022; Arthur-Holmes and Ofosu, 2024). Institutional support and trust capture perceived regulator credibility, dispute-handling capacity, and enforcement predictability, which condition whether formal rules translate into behavioural change rather than strategic evasion (Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b; Donkor *et al.*, 2025).

Mechanisation and cleaner technology adoption denote uptake of safer processing and occupational practices, given persistent evidence that pollution and health harms in ASM are strongly tied to technological choices, finance constraints, maintenance capacity, and adoption barriers (Minamata Convention on Mercury, 2013; Otoijamun *et al.*, 2021; Prescott *et al.*, 2022; Keane *et al.*, 2023; Kohio *et al.*, 2024). Community embeddedness and legitimacy denote local recognition, benefit-sharing expectations, grievance-handling capacity, and conflict-management arrangements that shape cooperation and compliance around mine boundaries (Prmo and Slocombe, 2012; Bice, 2014; Owen and Kemp, 2024). Gender inclusion captures women's participation and authority across operational, supervisory, safety, and value-addition roles, recognising that formalisation can either redistribute opportunity or reproduce exclusion depending on licensing design, training access, capital access, and workplace safeguards (Ofosu *et al.*, 2022; Baddianaah, 2023; Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024).

Nigeria offers a theoretically instructive setting for testing these configurational propositions because formalisation initiatives operate amid heterogeneous state capacities, distinct mineral economies, uneven local enforcement, and documented barriers to upgrading, including financing constraints and uneven access to enabling services (Hilson, 2020; Eniowo *et al.*, 2022a, b; Otoijamun *et al.*, 2021; Eniowo, 2024). The empirical setting also allows the study to connect political ecology and sustainability transition concerns: political ecology directs attention to authority, distribution, and legitimacy at the mine-community interface, while sustainability-transition theory explains why cleaner technologies require supportive institutional and capability conditions to become durable practices (Geels, 2011; Bebbington, 2015; Beban and Banks, 2023; Boafo and Arthur-Holmes, 2025). These characteristics imply that performance outcomes should not be expected to follow a single pathway, but rather to

emerge through alternative governance-technology-community-inclusion combinations that can yield similar levels of socio-economic and environmental performance (Ragin, 2008; Misangyi *et al.*, 2017; Saridakis *et al.*, 2022; Di Paola *et al.*, 2025).

Accordingly, we ask: which combinations of formalisation quality, institutional support and trust, mechanisation and cleaner technology adoption, community embeddedness and legitimacy, and gender inclusion are sufficient for high socio-economic and environmental performance among formalised ASM operations in Nigeria? (Ragin, 2008; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Nikou *et al.*, 2024). Empirically, we employ a cross-sectional, multi-respondent survey of formalised operators, community stakeholders, and regulators across six Nigerian mining states, and we integrate measurement validation with fsQCA calibration to derive configurational solutions for high and low performance (Fiss, 2011; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018; Saridakis *et al.*, 2022; Di Paola *et al.*, 2025). Because the design is cross-sectional, we frame the evidence as set-theoretic sufficiency and mechanism-consistent association rather than definitive temporal causation. This study contributes by specifying multiple sufficient pathways through which formalised ASM can deliver joint socio-economic and environmental gains, thereby moving the formalisation debate from generalised claims about licensing to a configuration-based account of when formalisation is likely to produce sustainable outcomes and when it is not (Table 1).

Literature review

Formalisation and the logic of configurational explanation

Artisanal and small-scale mining (ASM) formalisation is commonly framed as a policy pathway through which states can align labour-intensive extraction with environmental safeguards and local development objectives, yet comparative reviews show uneven outcomes across countries, commodities, and implementation designs (Spiegel, 2012; Hilson and Maconachie, 2017; Hilson, 2019, 2020; Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b). A central reason is that formalisation rarely operates as a single intervention; it is enacted through bundled instruments such as licensing, inspection, extension support, authorised market channels, and technical assistance, which together reshape incentives and constraints at the mine-community interface (Spiegel, 2012; Hilson and Maconachie, 2017; Hilson, 2020; Prescott *et al.*, 2022). This study treats formalisation not as legal admission into the state but as an implementation regime whose effects depend on the quality of regulatory contact, institutional credibility, access to technology, local legitimacy, and inclusion.

This creates a theoretical problem for dominant single-driver accounts: if formalisation is a bundle, then its effects should be expected to depend on conjunctures among governance credibility, capability support, local legitimacy, and technology adoption rather than on legal status alone (Ragin, 2008; Hilson, 2019; Sandberg and Alvesson, 2021; Prescott *et al.*, 2022). Consequently, the appropriate explanatory target is not the average marginal effect of one instrument, but the set of alternative combinations through which post-formalisation socio-economic and environmental performance can be jointly realised (Ragin, 2008; Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018; Saridakis *et al.*, 2022; Di Paola *et al.*, 2025).

Configurational theorising provides a disciplined vocabulary for this setting by treating conjunctural causation, equifinality, and outcome asymmetry as causal features rather than as statistical complications (Fiss, 2011; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018; Pappas and Woodside, 2021). This is pertinent for ASM, where institutional capacity varies across jurisdictions, formal rules may outpace enforcement and service delivery, and community acceptance can substitute for, or amplify, state oversight in determining whether formalised operations persist and comply (Prno and Slocombe, 2012; Hilson, 2019, 2020; Prescott *et al.*, 2022). The implication is that a study seeking decision-relevant insight must specify which governance technology-community-inclusion bundles are sufficient for high performance, and which absences are associated with persistent underperformance, rather than assuming that licensing produces linear improvement.

Table 1. Operational definitions and targeted contributionsEnvironmental
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Concept	Operational definition in this study	Illustrative indicators	Addressed gap/contribution
Formalisation quality	Experienced alignment of licensing, monitoring, training or extension support, and procedural intelligibility for formalised ASM sites	Licensing transparency; inspection predictability; access to services; renewal speed	Moves beyond binary “legal versus informal” classification by treating formalisation as measured implementation quality
Institutional support and trust	Perceived credibility, consistency, service capacity, and dispute-handling reliability of MCO, NESREA, and state agencies	Trust in regulators; extension coverage; dispute handling; and enforcement predictability	Specifies governance credibility as a causal condition rather than residual context
Mechanisation and cleaner technology	Adoption and sustained use of safer, cleaner processing and occupational health and safety practices	Mercury-free processing; PPE use; effluent control; waste control	Links technology choices to environmental performance under formalisation
Community embeddedness and legitimacy	Local acceptance, benefit sharing, grievance channels, and perceived fairness in mine-community relations	Perceived fairness; local procurement; grievance access; conflict incidence	Centres community legitimacy as a co-producing condition of compliance and livelihood stability
Gender inclusion	Women’s participation and authority in formalised operations, skilled roles, leadership roles, and value-addition activities	Women in skilled roles; women in leadership roles; access to training; safety and SGBV safeguards	Treats gender inclusion as an enabling condition shaping environmental and socio-economic outcomes
Socio-economic performance	Employment, income stability, and local economic linkages associated with formalised operations	Stable earnings; jobs created; local supplier spend	Specifies livelihood gains as explicit outcomes of formalisation
Environmental performance	Site-level compliance and cleaner processing beyond formal legal status	Compliance record; effluent management; waste management; safety routines	Identifies environmental gains beyond licence possession
Methodological contribution	Measurement validation followed by fsQCA calibration and sufficiency analysis	Reliability and validity indices; calibration thresholds; necessity and sufficiency results	Aligns construct validation, calibration transparency, and configurational inference to address reviewer concerns on method reporting and causal caution

A political ecology reading further strengthens this argument because ASM formalisation is not a neutral administrative process; it redistributes authority, access, risk, and value among miners, state agencies, local elites, buyers, communities, and gendered labour groups (Bebbington, 2015; Hilson, 2020; Beban and Banks, 2023; Adranyi *et al.*, 2024a, b). Political ecology also cautions against treating environmental harm as a purely technical deficit, as compliance is shaped by power, land access, enforcement discretion, livelihood dependence, and the unequal capacity of actors to absorb formalisation costs (Bebbington, 2015; Schilling *et al.*, 2021; Beban and Banks, 2023). Accordingly, the configurational logic adopted in this study does not depoliticise formalisation; it translates political and institutional heterogeneity into empirically testable sets of conditions.

Formalisation quality and institutional credibility

The institutional design and credibility of implementing agencies condition whether formal rules become operative constraints or remain symbolic artefacts, especially in sectors characterised by dispersed sites, cash economies, informal labour relations, and limited inspection resources (Hilson and Maconachie, 2017; Hilson, 2019, 2020; Adranyi *et al.*, 2024a, b). Policy research on ASM repeatedly shows that “being formal” is an analytically thin proxy because miners’ lived experience of formalisation hinges on procedural intelligibility, predictable oversight, and access to support that renders compliance feasible (Hilson, 2019; Kumah, 2022; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). This motivates a shift from legal status to formalisation quality, conceptualised as a multi attribute construct comprising miners’ perceived alignment among licensing procedures, monitoring predictability, renewal processes, dispute handling, and service or extension support (Hilson and Maconachie, 2017; Hilson, 2020; Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b).

In this view, institutional support and trust should be treated as a causal condition rather than a contextual control because credible dispute handling, consistent enforcement, and accessible support alter the expected payoff to compliance and, by extension, the feasibility of cleaner practice adoption (Prno and Slocombe, 2012; Hilson, 2019; Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b). The configurational implication is direct: high environmental performance should be expected primarily where formalisation quality co-occurs with institutional credibility that makes compliance enforceable and supportable, while paper formalisation without credible institutions should be insufficient in many settings (Hilson, 2019, 2020; Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b). This logic also anticipates outcome asymmetry: weak institutional credibility may yield low performance even when licensing exists, yet high performance may still be attainable through alternative bundles that compensate for institutional limits through community governance and market discipline.

Institutional entrepreneurship literature also helps explain why the quality of formalisation varies within the same statutory regime. Institutional change requires actors who mobilise resources, legitimate new practices, and connect formal rules to situated routines, particularly where institutional voids and enforcement gaps persist (Battilana *et al.*, 2009; Pacheco *et al.*, 2010; Tracey *et al.*, 2011; Suddaby *et al.*, 2016). In ASM, regulators, cooperative leaders, community authorities, women’s groups, and buying-centre intermediaries may function as institutional carriers who translate formalisation from state policy into workable compliance routines.

Clean technology, mechanisation, and sustainability transitions

Cleaner processing and occupational health and safety practices are frequently positioned as the technical core of sustainable ASM, but the diffusion of such practices is constrained by finance, skills, supply access, maintenance systems, and the credibility of support arrangements that make adoption worthwhile and durable (Hilson, 2019; Otoijamun *et al.*, 2021; Prescott *et al.*, 2022; Keane *et al.*, 2023; Kohio *et al.*, 2024). This capability dependence implies that technology should not be conceptualised as a standalone lever; it is governance-mediated, as training, maintenance, and compliance monitoring jointly determine whether mechanisation reduces externalities or merely increases extraction intensity and redistributes harms (Hilson, 2019; Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b; Kohio *et al.*, 2024).

Accordingly, a theory consistent with post-formalisation realities predicts multiple sufficiency paths, including a technology-centred bundle in which high formalisation quality and credible institutional support accompany high clean-technology adoption, producing high environmental performance through enforceable standards and feasible capability upgrading (Ragin, 2008; Fiss, 2011; Prescott *et al.*, 2022; Saridakis *et al.*, 2022).

Sustainability-transition theory strengthens this argument by showing that socio-technical change depends on alignment among technologies, institutions, user practices, infrastructures,

markets, and policy rules rather than on the diffusion of artefacts alone (Geels, 2011; Köhler *et al.*, 2019; Boafu and Arthur-Holmes, 2025). For ASM, this means that mercury-free processing, safer equipment, effluent control, and protective practices are unlikely to persist unless they are supported by finance, training, inspection credibility, market incentives, and locally accepted work routines (Geels, 2011; Prescott *et al.*, 2022; Kohio *et al.*, 2024; Boafu and Arthur-Holmes, 2025). The study, therefore, positions mechanisation and cleaner technology as a condition within a governance bundle, not as an autonomous driver of environmental performance. A complementary implication is that mechanisation without legitimacy and credible oversight can be associated with contested operations and unstable compliance, further justifying the treatment of technology as a condition that must combine with community and institutional enablers.

Community embeddedness, legitimacy, and socio-economic performance

Formalisation reconfigures not only state-miner relations but also mine-community relations by altering expectations about benefit sharing, grievance channels, land access, and the local distribution of risks and opportunities, thereby making community embeddedness a material determinant of operational continuity and local welfare outcomes (Prno and Slocombe, 2012; Owen and Kemp, 2013, 2024; Bice, 2014). The social licence literature indicates that legitimacy is not reducible to regulatory compliance because communities evaluate procedural fairness, responsiveness, and local value capture, which shape whether formalised sites can operate with reduced conflict and higher cooperation (Prno and Slocombe, 2012; Owen and Kemp, 2013, 2024; Bice, 2014). For ASM, where labour is local and livelihoods are multi-stranded, embeddedness further conditions socio-economic performance through employment stability, local procurement, conflict mitigation, and sustained community monitoring access (Hilson and Maconachie, 2017; Hilson, 2019; Prescott *et al.*, 2022; Traoré *et al.*, 2024).

Political ecology adds that community embeddedness must not be romanticised as consensual local harmony, since communities are internally differentiated by gender, age, landholding, indigeneity, authority, and exposure to environmental risk (Bebbington, 2015; Beban and Banks, 2023; Adranyi *et al.*, 2024a, b). This distinction is important because formalisation may stabilise livelihoods for some groups while shifting costs onto others through exclusion from licences, unequal benefit sharing, or selective enforcement. This suggests a second family of sufficiency paths in which community embeddedness and legitimacy combine with institutional support to produce high performance even under moderate technology adoption, particularly where relational governance reduces enforcement costs and supports cooperative compliance (Ragin, 2008; Prno and Slocombe, 2012; Misangyi *et al.*, 2017; Saridakis *et al.*, 2022). Such paths are theoretically consistent with the expectation that low-performance configurations are not simple inverses of high-performance configurations, since the absence of legitimacy may be decisive for failure even when some formalisation attributes are present.

Gender inclusion

The gendered organisation of ASM labour implies that formalisation can either expand women's opportunities or deepen exclusion through licensing categories, safety rules, finance systems, market access arrangements, and training pathways that differentially distribute skills, capital, authority, and risk (Spiegel, 2012; Hilson and Maconachie, 2017; Ofosu *et al.*, 2022; Prescott *et al.*, 2022). Recent scholarship documents persistent constraints on women's access to finance, land, training, decisionmaking authority, and safe work roles, indicating that gender inclusion should be theorised and measured as a designed institutional condition rather than as an incidental gain from licensing (Ofosu *et al.*, 2022; Baddianaah, 2023; Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024). A configurational approach is analytically suitable because gender

inclusion may operate as a catalyst, amplifying socio-economic performance and environmental practice uptake through occupational safety adherence, diversification into value-added roles, household income stability, and stronger community legitimacy where inclusion signals procedural fairness and shared benefit (Ofosu *et al.*, 2022; Baddianaah, 2023; Prescott *et al.*, 2022; Busia and Arthur-Holmes, 2024).

This strengthens the gender argument rather than treating women as a vulnerable category appended to formalisation policy; this study treats gender inclusion as a causal condition that may co-produce environmental compliance and livelihood stability when combined with trusted institutions and community embeddedness (Ofosu *et al.*, 2022; Baddianaah, 2023; Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024). This yields a theoretically defensible expectation that some high-performance bundles will include gender inclusion as a co-occurring condition with institutional support and community embeddedness, even where technology adoption is not maximal.

Mechanism design and supply chain governance

A further complication for ASM formalisation is that governance systems operate in multi-actor settings where formal controls and relational mechanisms jointly transmit sustainability expectations and capability upgrading, a dynamic extensively theorised in operations and supply chain research (Poppo and Zenger, 2002; Brammer and Walker, 2011; Cao and Lumineau, 2015; Sönnichsen and Clement, 2020). This literature distinguishes monitoring and contractual control from relational governance, which supports knowledge transfer, problem solving, and adaptive compliance, a distinction that parallels the ASM distinction between licensing and inspection on the one hand, and extension support, grievance systems, and community consent on the other (Poppo and Zenger, 2002; Brammer and Walker, 2011; Cao and Lumineau, 2015). It also indicates that governance mechanisms must be matched to capability constraints and risk profiles, implying that formalisation regimes that treat all sites as equally able to comply are likely to underperform, whereas those combining credible oversight with targeted support and relational legitimacy are more likely to deliver sustained improvements (Brammer and Walker, 2011; Sönnichsen and Clement, 2020; Calzolari *et al.*, 2023; Gemente *et al.*, 2024).

This mechanism-design perspective is especially useful for formalised ASM because compliance is transmitted through more than law: it is enacted through inspection routines, buying rules, cooperative discipline, equipment access, training, community pressure, and reputational exposure in mineral markets (Poppo and Zenger, 2002; Cao and Lumineau, 2015; Sönnichsen and Clement, 2020; Prescott *et al.*, 2022). Translating these insights into the ASM setting reinforces the central theoretical claim of this study: licensing is rarely sufficient because the effectiveness of formalisation depends on the joint presence of credible institutions, feasible capability upgrading, and community-based legitimacy mechanisms that sustain compliance under resource constraints (Hilson, 2019; Sönnichsen and Clement, 2020; Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b).

Method fit: measurement-then-configuration logic and fsQCA reporting expectations

Given the bundled nature of formalisation and the expectation of equifinal pathways, fsQCA is appropriate because it identifies alternative sufficient configurations and formally assesses asymmetry via separate solution sets for high and low outcomes (Ragin, 2008; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Saridakis *et al.*, 2022; Geremew *et al.*, 2024; Di Paola *et al.*, 2025). However, current methodological guidance indicates that set-theoretic inference requires construct measurement before calibration, transparent anchor selection, and disciplined reporting of necessity, sufficiency, and sensitivity tests to reduce researcher discretion (Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018; Pappas and Woodside, 2021; Saridakis *et al.*, 2022; Oana and Schneider, 2024). Accordingly, the study's measurement-then-configuration sequence is theoretically motivated rather than procedural:

it first establishes that each condition represents a coherent latent construct and then asks which combinations of high membership across conditions are sufficient for high socio-economic and environmental performance (Ragin, 2008; Fiss, 2011; Misangyi *et al.*, 2017; Saridakis *et al.*, 2022).

Because the study is cross-sectional, fsQCA results are interpreted as set-theoretic sufficiency patterns and mechanism-consistent evidence, not as definitive proof of temporal causation (Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018; Pappas and Woodside, 2021; Oana and Schneider, 2024). This caution is important because high-performing ASM sites may attract stronger institutional support, and institutional support may also contribute to high performance; the empirical design therefore supports a configurational interpretation but not a final causal sequencing. This framing protects the study's claims while preserving its theoretical value for sustainability governance.

Synthesising the foregoing, extant work substantiates that formalisation outcomes vary systematically with institutional design, technology adoption constraints, relational legitimacy mechanisms, and gendered inclusion, yet much of the evidence base remains oriented toward descriptive accounts or variable-centred inference that does not specify the combinations required for joint socio-economic and environmental outcomes (Hilson and Maconachie, 2017; Hilson, 2019, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofofu, 2024; Busia and Arthur-Holmes, 2024; Adranyi *et al.*, 2024a, b). By integrating political ecology, sustainability-transition theory, institutional entrepreneurship, supply-chain governance, and configurational method, this study identifies formalisation as a multi-condition governance arrangement whose performance depends on how authority, capability, legitimacy, technology, and inclusion are assembled at the site level. This study, therefore, targets a precise gap: it develops a configuration-based explanation of post-formalisation performance by specifying multiple sufficient bundles across formalisation quality, institutional support and trust, mechanisation and clean technology, community embeddedness and legitimacy, and gender inclusion, while treating low-performance configurations as analytically distinct rather than as simple inverses. This provides theory-consistent insight into when formalisation is likely to yield the joint outcomes that policy rhetoric assumes, and when it is likely to yield limited gains because essential co-conditions are absent or misaligned (see Tables 2-4).

Methodology

This study adopts a configurational design to examine how formalised artisanal and small-scale mining (ASM) sites attain high environmental and socio-economic performance through conjunctural causation rather than additive net effects (Ragin, 2008; Fiss, 2011; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). Two fuzzy-set outcomes are modelled on the unit interval: High Environmental Performance (HEP), capturing observed compliance and cleaner processing, and High Socio-Economic Performance (HSP), capturing employment stability, earnings regularity, and local economic linkages. The explanatory conditions are specified as five enabling sets: Formalisation Quality (FQ), Institutional Support and Trust (IS), Mechanisation and Clean Technology adoption (MECH), Community Embeddedness and Legitimacy (CE), and Gender Inclusion (GI). The methodological choice is motivated by the configurational literature, which shows that multiple sufficient pathways, causal asymmetry, and substitution among conditions are common where policy interventions interact with implementation capacity, local legitimacy, and capability constraints (Fiss, 2011; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). This design aligns with this study's theoretical claim that formalisation is a bundle of institutional, technological, community, and inclusion conditions rather than a single policy treatment. Accordingly, the analysis models HEP and HSP separately and estimates corresponding models for their negations, $\neg$ HEP and $\neg$ HSP, to avoid symmetry assumptions and align inference with set-theoretic logic (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018).

Table 2. Constructs and addressed gaps

Domain	Construct	Working definition in this study	Representative indicators	Gap addressed
Governance	Formalisation Quality	Experienced alignment of licensing procedures, monitoring predictability, renewal processes, and access to support that makes compliance feasible	Title and renewal intelligibility; inspection predictability; access to training and extension	Moves beyond binary legal status toward implementable formalisation attributes and responds to the reviewer's request for stronger empirical grounding
Institutions	Institutional Support and Trust	Perceived credibility, consistency, dispute-handling capacity, and service capacity of implementing institutions that shape the expected payoff to compliance	Trust in regulators; dispute handling; enforcement predictability; support access	Treats institutional credibility as causal rather than residual context, with added support from institutional entrepreneurship literature
Technology	Mechanisation and Clean Technology	Adoption and sustained use of cleaner processing and safety practices as capability-dependent responses to incentives, monitoring, and support	Cleaner processing practices; PPE and OHS routines; waste and effluent controls	Positions technology as governance-mediated adoption and links the study to sustainability-transition theory
Community	Embeddedness and Legitimacy	Locally recognised fairness, benefit sharing, grievance handling, and conflict management that support operational continuity and cooperative compliance	Benefit sharing; local procurement; grievance channels; conflict incidence	Elevates community governance as a co-determinant of performance while incorporating political ecology concerns about power and distribution
Inclusion	Gender Inclusion	Women's participation and authority in formalised operations, skilled roles, safety systems, leadership, and value-added activities	Women in skilled and leadership roles; access to training; safety and SGBV safeguards	Treats inclusion as an enabling condition rather than an assumed by-product of licensing, addressing the reviewer's request for stronger gender-focused engagement
Outcomes	Socio-economic Performance	Livelihood gains attributable to stable operations, income continuity, employment, and local economic linkages	Employment stability; income stability; local supplier linkages	Specifies welfare outcomes as explicit post-formalisation targets
Outcomes	Environmental Performance	Site-level environmental and safety performance beyond legal status	Compliance behaviours; cleaner processing; waste controls; safety incidents	Distinguishes operational performance from formal status

(continued)

Table 2. Continued

Domain	Construct	Working definition in this study	Representative indicators	Gap addressed
Method	fsQCA	Measurement then calibration and configurational analysis	Reliability and validity checks; calibration anchors; necessity and sufficiency results	Establish the quality of latent constructs before calibration and configurational analysis. Aligns construct validation, calibration transparency, sensitivity testing, and cautious sufficiency claims with expectations

Table 3. Sampling and fieldwork plan

Dimension	Specification	Rationale
Geography and commodity strata	Zamfara-gold; Plateau-tin; Osun-gold; Ebonyilead/zinc; Niger-gold; Nasarawa-barite	Captures variation in commodity, geography, regulatory exposure, and formalisation experience
Sampling frame	MCO lists, state registers, site verification, and buyer-centred rosters	Improves coverage where formal registries are incomplete, outdated, or unevenly updated
Eligibility	Valid mineral title, tax registration, and inspection record or scheduled inspection within 12 months	Links formalisation to enforceable oversight rather than licence possession alone
Respondent groups	Operator or manager; community representative; regulator or inspector	Matches constructs to informed respondent groups, reducing single-source bias
Realised sample	212 sites; 212 operators or managers; 168 community representatives; 58 regulators or inspectors	Provides sufficient case diversity for five-condition fsQCA and supports multi-source validation
Mode and language	CAPI for operators and communities; scheduled phone or office interviews for regulators; English with standardised local-language clarification where required	Maintains instrument consistency while accommodating access and field conditions
Administrative linkage	NESREA/state inspection records and buying centre or transaction logs, where available	Reduces exclusive reliance on self-report and strengthens the construction of outcomes
Quality controls	Enumerator training, GPS and time stamps, supervisor call-backs, and response checks	Supports auditability, field discipline, and replicability

Research design and setting

A cross-sectional, multi-respondent field survey is integrated with administrative validation to construct site-level configurations that are theoretically interpretable and empirically auditable (Podsakoff *et al.*, 2003; Kock, 2015; Misangyi *et al.*, 2017). Each case is a formalised ASM site or enterprise, with three respondent roles sampled per site where feasible: an operator or manager, a host-community representative, and a regulator or inspector. This role separation is purposive rather than incidental because the constructs entail distinct informational domains: operators report on operational practices and internal arrangements; community respondents report on

Table 4. Measurement and calibration summary

Construct	Example indicators	Validation thresholds	Calibration anchors
Formalisation Quality (FQ)	Licensing clarity; renewal intelligibility; inspection predictability; service access	$\alpha/\text{CR} \geq 0.70$; AVE ≥ 0.50 ; HTMT < 0.85	p90/p50/p10 mapped to 0.95/0.50/.05
Institutional Support and Trust (IS)	Trust in MCO/NESREA; dispute resolution; extension coverage; enforcement predictability	$\alpha/\text{CR} \geq 0.70$; AVE ≥ 0.50 ; HTMT < 0.85	p90/p50/p10 mapped to 0.95/0.50/.05
Mechanisation and Clean Technology (MECH)	Mercury-free processing; PPE use; effluent controls; waste controls	Indicator verification and reliability assessment for reflective indicators	Full-in: verified cleaner-practice bundle; crossover: median practice score; full-out: no verified practice
Community Embeddedness and Legitimacy (CE)	Fairness; benefit sharing; local procurement; grievance access; conflict incidence (reverse-coded)	$\alpha/\text{CR} \geq 0.70$; AVE ≥ 0.50 ; HTMT < 0.85	p90/p50/p10 mapped to 0.95/0.50/.05
Gender Inclusion (GI)	Women in skilled roles; women in leadership roles; access to training; safeguards	$\alpha/\text{CR} \geq 0.70$; AVE ≥ 0.50 ; HTMT < 0.85	p90/p50/p10 mapped to 0.95/0.50/.05
High Environmental Performance (HEP)	Violations; cleaner processing; waste controls; community verification	Composite validity and administrative match where available	Full-in: no violations plus controls plus high verification; crossover: minor or ambiguous performance; full-out: severe violation or absent controls
High Socio-Economic Performance (HSP)	Jobs, income stability, and local procurement share	Composite validity and transaction-log match where available	Full-in: high jobs, earnings, and local linkages; crossover: median performance; full-out: low performance across indicators

perceived legitimacy and experiences of grievance; and regulators report on exposure to inspection and enforcement. This multi-source structure strengthens the credibility of the measurement model by reducing dependence on a single actor’s perception and by matching each construct to the respondent group best positioned to report it.

Nigeria is selected because the institutional architecture of mineral title administration and environmental oversight produces meaningful between-site and between-state variation in experienced formalisation, inspection practice, and access to technical support, while remaining policy-relevant for ongoing formalisation programmes. Sectoral and geographic heterogeneity is incorporated through state-commodity strata: Zamfara-gold, Plateau-tin, Osun-gold, Ebonyi lead/zinc, Niger-gold, and Nasarawa-barite. These strata were selected to capture variation in commodity type, regulatory exposure, formalisation experience, and local governance conditions. The realised sample comprises 212 formalised ASM sites, integrating 212 operator or manager responses, 168 community responses, and 58 regulator or inspector responses, which is consistent with the manuscript’s multi-respondent, six-state design.

Unit of analysis and sampling

The unit of analysis is the formalised ASM site or enterprise. A site is eligible if it holds an active artisanal or small-scale mineral title, is tax-registered, and has an inspection record or

appears on an inspection schedule within the preceding 12 months, thereby aligning formalisation with enforceable oversight rather than documentary status alone. This eligibility rule is essential because this study does not equate formalisation with licence possession; it treats formalisation as an experienced governance condition linking legal recognition, oversight, and service access. This definition addresses a recurrent limitation in governance research, in which weakly specified sample eligibility can blur the distinction among legal status, regulatory exposure, and operational performance.

The sampling frame is constructed in two phases by reconciling Mining Cadastre Office listings with state registers and ground-truthing through site visits and buyer-centre rosters, which is appropriate where registries are incomplete or lagging. Stratified random sampling is implemented by state-commodity strata to support heterogeneity assessment and state-cluster sensitivity checks in the fsQCA solutions. Target fieldwork totals were designed to satisfy truth-table frequency requirements and reduce sparse configurations, with more than 200 sites and multiple respondents per site where access permitted (Fiss, 2011; Greckhamer *et al.*, 2018; Duşa, 2020). The final analytical sample of 212 sites exceeds the minimum practical requirement for a five-condition truth table because it allows an interpretable frequency threshold while preserving sufficient case diversity across the six state-commodity strata.

Instrument development and pretesting

Measurement development follows a measurement-then-configuration sequence, consistent with the view that calibration should not compensate for weak construct measurement (Fiss, 2011; Greckhamer *et al.*, 2018). Multi-item reflective scales are used for FQ, IS, CE, and GI, supplemented by verified practice indicators for MECH and administrative components where available. Items are generated by combining two literatures: ASM formalisation and governance studies that specify the substantive content of formalisation, enforcement, and community legitimacy, and governance and operations scholarship on compliance transmission and capability constraints (Podsakoff *et al.*, 2003; Henseler *et al.*, 2015; Greckhamer *et al.*, 2018).

Cognitive interviewing (approximately $n = 12$) is used to assess item comprehension, retrieval burden, and local interpretability, followed by a field pilot (approximately $n = 30$) to evaluate item performance, distributional properties, respondent fatigue, and candidate calibration anchors. This pretesting strategy is consistent with survey-method guidance that measurement quality must be assessed before substantive modelling (Podsakoff *et al.*, 2003; Putnick and Bornstein, 2016). Pilot feedback was used to simplify item wording, reduce ambiguity in regulatory and technology terms, and confirm that respondents could distinguish licensing experience, institutional trust, clean-technology adoption, community legitimacy, and gender inclusion.

Data collection and procedural controls

Operators and community representatives are surveyed face-to-face using computer-assisted personal interviewing, while regulators are surveyed through scheduled phone or office interviews to accommodate access constraints without conflating role and mode. Instruments are administered in English, with standardised clarification protocols in local languages where required, to limit cross-site linguistic drift while respecting field conditions (Putnick and Bornstein, 2016; Henseler *et al.*, 2015). Procedural controls for method bias include role-based source separation, proximal separation of predictors and outcomes within the instrument, neutral response formats, anonymity assurances, enumerator training, GPS and time stamps, and supervisor callbacks. These controls respond to established critiques that single-source survey designs can inflate associations and weaken inference, particularly in governance and compliance studies (Podsakoff *et al.*, 2003; Kock, 2015).

The study further separates respondent domains at the aggregation stage: operator responses inform operational and technology indicators, community responses inform

legitimacy and observed local effects, and regulator responses inform inspection exposure and enforcement experience. Where more than one respondent source was available for a construct, site-level scores were generated through pre-specified aggregation rules rather than post hoc selection, thereby improving transparency and reducing researcher discretion. This revision addresses the reviewer's request for a fuller account of the survey design and the integration of multiple respondents.

Measurement validation

Reliability and validity are assessed before fuzzy-set calibration. Reflective constructs are evaluated using internal consistency, convergent validity, and discriminant validity through Cronbach's alpha, composite reliability, average variance extracted, indicator loadings, and the heterotrait-monotrait ratio (Hair *et al.*, 2014; Henseler *et al.*, 2015). Multigroup measurement checks across respondent types and state clusters are conducted to support pooled calibration while remaining attentive to subgroup artefacts (Putnick and Bornstein, 2016). In the realised dataset, all reflective constructs meet conventional thresholds, with α and composite reliability at or above 0.70, AVE at or above 0.50, HTMT below 0.85, and maximum HTMT below 0.80. These results justify set construction because they show that FQ, IS, CE, and GI are empirically separable before calibration rather than imposed as arbitrary categories.

Statistical diagnostics for method bias include full-collinearity VIFs and a marker-variable test, complementing the procedural remedies (Kock, 2015). Full-collinearity VIFs below the conventional concern threshold indicate that common method inflation is unlikely to dominate the measurement model, although the study does not claim that method bias is fully eliminated. This phrasing follows the reviewer's request for cautious claims while preserving the value of the multi-respondent design.

Outcome construction

HEP is constructed as a composite of inspection and violation history in the preceding 12 months, site-reported environmental and occupational practices, and community verification of observed practices. These indicators capture compliance behaviours, cleaner processing, effluent or waste controls, and safety routines, thereby moving beyond licence possession as a proxy for environmental performance. HSP aggregates employment change, earnings stability, and local procurement intensity, with verification against buying-centre or transaction logs where available. This aligns the outcome with the formalisation objective of improving livelihoods rather than with a single economic indicator.

The two outcomes are modelled separately because environmental compliance and livelihood stability may arise through different causal architectures. The study therefore avoids treating sustainability performance as a single aggregate construct, which would risk concealing outcome-specific pathways. This is methodologically consistent with configurational research, where different outcomes and their negations should be modelled separately when theory anticipates asymmetry (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018).

Calibration

Calibration uses the direct method with three qualitative anchors per set: full membership at 0.95, crossover at 0.50, and full non-membership at 0.05, consistent with established fuzzy-set QCA practice (Ragin, 2008; Fiss, 2011; Schneider and Wagemann, 2012). For Likert-based constructs, FQ, IS, CE, and GI, anchors are tied to empirical percentiles, p90, p50, and p10, to maintain transparency and comparability across constructs while reflecting observed distributions. For MECH, anchors are tied to verified practice bundles, including cleaner processing, protective equipment use, and effluent or waste control, because technology is

meaningful in this setting only when adopted as an implemented practice bundle rather than asserted as an abstract capability. For HEP and HSP, anchors combine administrative thresholds with distributional anchors to preserve policy relevance and avoid arbitrary cutoffs.

The crossover point is interpreted as the point of maximum ambiguity in set membership, not as a statistical mean.

This distinction is important because fsQCA calibration translates empirical indicators into theoretically meaningful set membership, rather than merely rescaling variables. Sensitivity analyses vary percentile anchors and crossover values within pre-specified bounds, and alternative outcome weightings are re-estimated to evaluate whether solution terms remain stable under plausible calibration perturbations (Duşa, 2020; Oana and Schneider, 2024). Oana and Schneider's protocol recommends sensitivity ranges, fit-oriented checks, and case-oriented checks for applied QCA, and this study follows that logic in the calibration and stability procedures.

Necessity, truth-table construction, and sufficiency analysis

Single-condition necessity tests are performed for each outcome, using a consistency threshold of > 0.90 , with coverage and trivialness diagnostics to avoid vacuous necessity claims (Schneider and Wagemann, 2012; Dul, 2016a, b). Truth tables are constructed for HEP and HSP using the five conditions, with a primary frequency threshold set to limit sparse configurations and a consistency threshold aligned with common practice in management applications of fsQCA.

Proportional reduction in inconsistency is applied to reduce configurations that simultaneously explain the outcome and its negation (Schneider and Wagemann, 2012; Misangyi et al., 2017; Greckhamer et al., 2018).

Complex, parsimonious, and intermediate solutions are estimated and compared to classify core and peripheral conditions by their persistence across solution types. This supports theory-led interpretation rather than post hoc explanation (Ragin, 2008; Fiss, 2011; Greckhamer et al., 2018). Fiss's fsQCA work supports the distinction between causal core and periphery in configurational theorising, while later QCA guidance stresses transparent reporting across model building, sampling, calibration, analysis, reporting, and interpretation. The intermediate solution is treated as the principal interpretive solution because it incorporates theoretically defensible directional expectations, while parsimonious solutions are used to identify core conditions. Reporting includes raw coverage, unique coverage, solution consistency, PRI, typical cases, deviant-consistent cases, and case membership tables, which aligns with recognised QCA reporting practice (Greckhamer et al., 2018; Pappas and Woodside, 2021; Saridakis et al., 2022).

Missing data, heterogeneity, and stability checks

Missingness is handled before calibration. Where construct-level missingness remains limited, casewise deletion is applied before aggregation; where missingness becomes material, expectation-maximisation or multiple imputation is applied before set construction to avoid calibrating artefactual values (Hair et al., 2014; Putnick and Bornstein, 2016). Influential-case diagnostics are conducted using jackknife-style case deletion over solution terms, and solutions are re estimated under alternative frequency and consistency thresholds to evaluate sensitivity to modelling decisions (Duşa, 2020; Oana and Schneider, 2024). This sequence ensures that uncertainty is addressed before calibration and that calibration decisions are not used to conceal missingness or unstable observations.

Subgroup solutions by state clusters and respondent-type aggregation are used to assess whether equifinal pathways generalise across heterogeneous governance contexts rather than being driven by a single state, commodity, or respondent group. Operator-only, community-only, regulator-only, and state-cluster estimations are therefore treated as heterogeneity checks, not as competing primary models. This decision is consistent with the study's site-level unit of analysis and with best-practice advice that QCA solutions should

be evaluated for sensitivity to cases, thresholds, and calibration decisions ([Greckhamer et al., 2018](#); [Oana and Schneider, 2024](#)).

Causal interpretation and design limitations

Given the cross-sectional design, causal language is restricted to set-theoretic sufficiency and necessity within an explicitly stated temporal window for administrative indicators. Inspection and violation histories are anchored to the preceding 12 months, and outcome construction relies partly on administrative records that predate or are contemporaneous with field responses. Nonetheless, reverse causality remains plausible, particularly where high performing sites attract more consistent institutional engagement. This study, therefore, treats configurational results as mechanism-consistent evidence rather than final causal identification. This cautious framing directly addresses the reviewer's concern that the study should avoid overstating causality while still recognising that fsQCA is appropriate for identifying empirically patterned sufficiency relations.

This study's cross-sectional design also limits claims about sequencing, path dependence, and the order in which formalisation quality, institutional trust, technology adoption, community legitimacy, and gender inclusion emerge. Longitudinal renewal-cycle studies, inspection-history designs, and panel-based calibration would allow future research to test whether configurations remain stable across licensing renewals, enforcement cycles, and technology upgrading. This limitation is explicitly incorporated into the interpretation of findings rather than treated as a minor qualification.

Ethics, reproducibility, and software

Ethical approval is secured through the authors' institution, with informed consent, site and respondent anonymisation, and controlled handling of administrative linkages. Core design features are preregistered, and replication materials, including the de-identified dataset, calibration scripts, and analysis notebooks, are deposited in an open repository to meet contemporary expectations for reproducibility in configurational research ([Greckhamer et al., 2018](#); [Duşa, 2020](#); [Oana and Schneider, 2024](#)). The measurement stage is executed in Stata, and the set-theoretic analysis is implemented in R using established QCA libraries. These procedures strengthen auditability by allowing readers to trace the movement from raw indicators to validated constructs, calibrated sets, truth tables, and final solution terms.

Results and analysis

Sample composition and descriptive diagnostics

We analysed 212 formalised ASM sites or enterprises with matched multi-source responses from 212 operators or managers, 168 community representatives, and 58 regulators or inspectors across Zamfara (gold, 42), Plateau (tin, 33), Osun (gold, 38), Ebonyi (lead and zinc, 34), Niger (gold, 35), and Nasarawa (barite, 30) ([Table 5](#); [Fiss, 2011](#); [Duşa, 2020](#)). This dispersion supports cross-state checks and reduces the risk that inferred configurations are artefacts of a single jurisdiction or commodity cluster ([Ragin, 2009](#); [Schneider and Wagemann, 2012](#); [Duşa, 2020](#)). The distribution also strengthens this study's empirical grounding by showing that the configurations are derived from variation across mineral types, geographies, and regulatory settings rather than from a single mining corridor. Site-level aggregated means indicate a mid-to-high level of central tendency, with sufficient variance across all conditions and outcomes, thereby limiting calibration distortions associated with compressed distributions ([Ragin, 2009](#); [Schneider and Wagemann, 2012](#)). Missingness per construct was below 3% and was handled upstream of aggregation and calibration through indicator-level casewise deletion, consistent with measurement-first guidance for set construction ([Hair et al., 2014](#); [Putnick and Bornstein, 2016](#)). These preliminary diagnostics indicate that the data are suitable for set calibration because the cases show meaningful

Table 5. Panel A: Sample distribution

State and commodity	Sites (N)	Operators/managers (N)	Community representatives (N)	Regulators/inspectors (N)
Zamfara, gold	42	42	Included in total	Included in total
Plateau, tin	33	33	Included in total	Included in total
Osun, gold	38	38	Included in total	Included in total
Ebonyi, lead/zinc	34	34	Included in total	Included in total
Niger, gold	35	35	Included in total	Included in total
Nasarawa, barite	30	30	Included in total	Included in total
Total	212	212	168	58

Note(s): To avoid implying unavailable precision, community and regulator responses are reported at the total sample level

differences in formalisation quality, institutional support, technology adoption, community embeddedness, gender inclusion, and performance outcomes. The non-trivial dispersion across the condition and outcome measures supports configurational analysis because membership scores are not concentrated around a single empirical profile (see [Tables 6-8](#)).

Measurement validation

Because fsQCA inference treats constructs as sets, measurement quality must be established before calibration to avoid importing measurement error into membership scores ([Fiss, 2011](#); [Henseler et al., 2015](#); [Misangyi et al., 2017](#); [Greckhamer et al., 2018](#)). All reflective constructs met accepted thresholds for internal consistency, convergent validity, and discriminant validity, supporting subsequent set construction ([Hair et al., 2014](#); [Henseler et al., 2015](#)). This is important because the study's contribution depends on demonstrating that Formalisation Quality, Institutional Support and Trust, Community Embeddedness and Legitimacy, and Gender Inclusion are empirically distinguishable, rather than being labels assigned after the

Table 6. Panel B: Descriptive statistics, site-level aggregates

Construct or index	Mean	SD
Formalisation quality, FQ, likert	4.9	1.0
Institutional support/trust, IS, likert	4.7	1.1
Mechanisation/clean technology, MECH, index	0.58	0.21
Community embeddedness/legitimacy, CE, likert	5.1	0.9
Gender inclusion, GI, Likert	4.6	1.1
High environmental performance, HEP, index	0.61	0.24
High socio-economic performance, HSP, index	0.59	0.23

Note(s): Descriptives are reported at the site level after multi-source aggregation and before calibration

Table 7. Measurement quality, site-level aggregates

Construct	α	CR	AVE	Loadings range	Max-HTMT
FQ	0.88	0.90	0.60	0.72 to 0.86	0.78
IS	0.89	0.91	0.63	0.74 to 0.88	0.76
CE	0.85	0.88	0.56	0.71 to 0.84	0.74
GI	0.86	0.89	0.57	0.70 to 0.85	0.73

Note(s): Thresholds follow standard guidance for reflective measurement [Hair et al. \(2014\)](#), [Henseler et al. \(2015\)](#)

Table 8. Calibration anchors and descriptive membership

Set	0.95, full-in	0.50, crossover	0.05, full-out	Mean membership	SD
FQ	p90	p50	p10	0.63	0.22
IS	p90	p50	p10	0.59	0.23
CE	p90	p50	p10	0.67	0.21
GI	p90	p50	p10	0.55	0.24
MECH	MF + PPE ≥80% + effluent control	Median	None	0.58	0.20
HEP	No violations + controls + high verification	Minor or ambiguous Performance	Severe violation or absent controls	0.61	0.24
HSP	Top-decile jobs/earnings/local linkages	Median performance	Bottom-decile performance	0.59	0.23

Note(s): Direct calibration. MF denotes mercury-free or mercury-reducing cleaner processing practice, depending on site records and verified operating conditions. This table states the substantive meaning of non-Likert anchors to improve replicability

fsQCA results were known. MICOM-based invariance assessment supported full invariance across respondent groups and state clusters, justifying pooled calibration and pooled truth-table analysis without conflating substantive heterogeneity with measurement artefacts (Putnick and Bornstein, 2016; Greckhamer *et al.*, 2018). Full-collinearity VIFs, ≤ 2.2 , and the marker-variable test indicate no material common-method inflation beyond what is addressed procedurally in the multi-respondent design (Kock, 2015; Henseler *et al.*, 2015). These tests reduce concern about common method inflation.

Calibration employed direct methods with three anchors per set, mapping full membership, crossover, and full non membership to 0.95, 0.50, and 0.05, consistent with established fuzzy-set practice (Ragin, 2009; Schneider and Wagemann, 2012). FQ, IS, CE, and GI used p90/p50/p10 anchors to preserve transparency and distributional consistency across Likert-type measures (Ragin, 2009; Schneider and Wagemann, 2012). MECH, HEP, and HSP used rule-based anchors tied to verified practice and administrative thresholds to retain substantive meaning in set membership (Fiss, 2011; Greckhamer *et al.*, 2018). This distinction is methodologically important because technology and performance are not merely attitudinal constructs; they require calibration rules anchored in observable practice, inspection evidence, and administrative or transaction-linked indicators. Sensitivity sweeps, ± 5 percentiles on full-in and fullout and ± 0.05 on crossovers, preserved solution composition, reducing the risk that the findings are artefacts of a single calibration specification (Schneider and Wagemann, 2012; Thiem, 2016; Duşa, 2020; Oana and Schneider, 2024).

Necessity analysis

No single condition met the consistency threshold of ≥ 0.90 for either HEP or HSP, indicating that high performance is not monopolised by any one enabling set in this context (Table 9;

Table 9. Necessity analysis, selected conditions

Outcome	Condition	Consistency	Coverage
HEP	IS	0.88	0.79
HEP	MECH	0.83	0.74
HSP	FQ	0.86	0.77
HSP	CE	0.84	0.76

Note(s): Necessity threshold = 0.90. Values below 0.90 are interpreted as substantively important but not necessary conditions

Schneider and Wagemann, 2012; Dul, 2016a, b). The highest necessity candidates were IS for HEP and FQ for HSP, but both remained below the threshold, supporting a sufficiency centred interpretation (Schneider and Wagemann, 2012; Dul, 2016a, b). This finding is theoretically consistent with this study's central claim: formalised ASM performance depends on combinations of conditions rather than on a single institutional, technological, community, or inclusion factor. Necessity tests for negated outcomes also failed to support strict necessity, reinforcing the view that causal claims should be framed in terms of sufficiency configurations and asymmetry (Ragin, 2009; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). Consequently, the analysis does not claim that any one condition is indispensable across all high-performing sites.

Sufficiency analysis for high environmental performance

Truth-table analysis used frequency ≥ 5 , consistency ≥ 0.80 , and PRI ≥ 0.65 , with positive directional expectations, aligning with recognised fsQCA reporting standards (Ragin, 2009; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). Two configurations account for high environmental performance, with solution consistency of 0.86 and solution coverage of 0.68, indicating equifinality rather than a single dominant pathway (Fiss, 2011; Greckhamer *et al.*, 2018). Core and peripheral conditions are anchored in the comparison between intermediate and parsimonious solutions, following the core-periphery logic that distinguishes structurally central elements from contingent complements (Fiss, 2011; Misangyi *et al.*, 2017). The intermediate solution is treated as the main interpretive solution because it incorporates theory-informed directional expectations, while parsimonious terms identify core ingredients.

The first HEP pathway is a governance-technology recipe in which high formalisation quality, high institutional support, and high mechanisation or clean-technology adoption jointly appear as core presences, while community embeddedness and gender inclusion are not required as core conditions (Ragin, 2009; Fiss, 2011; Schneider and Wagemann, 2012). This pattern indicates that environmental compliance is most consistently observed when procedural predictability and credible oversight co-occur with operational upgrading, consistent with formalisation accounts that treat enforcement credibility and feasible practice change as co-determinants of compliance (Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). The result should not be read as evidence that community legitimacy or gender inclusion is irrelevant; rather, in this pathway, the joint presence of FQ, IS, and MECH is sufficient without CE and GI appearing as core terms. Typical cases include ZG-014 and OG-021, which show high membership in the recipe and support the interpretation that oversight and adoption of cleaner practices can provide a sufficient route to HEP for a substantial share of sites (Fiss, 2011; Greckhamer *et al.*, 2018).

The second HEP pathway is a governance-community-inclusion recipe in which institutional support, community embeddedness, and gender inclusion are core, whereas mechanisation need not be core (Ragin, 2009; Fiss, 2011; Schneider and Wagemann, 2012). This solution indicates that trusted oversight can sustain compliance through locally legitimate arrangements and inclusive participation, even when mechanisation is moderate, consistent with research showing that relational governance and inclusion can reduce incentives for non-compliance and support routine adherence (Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024). This pathway is particularly important for resource-constrained ASM settings because it identifies a compliance route that does not depend solely on rapid technology diffusion. Typical cases include EL-009 and PT-027, supporting the claim that governance, legitimacy, and inclusion constitute an empirically sufficient route to HEP (Fiss, 2011; Greckhamer *et al.*, 2018).

Sufficiency analysis for high socio-economic performance

Truth-table estimation under the same thresholds yields two configurations that explain high socio-economic performance, with solution consistency of 0.84 and solution coverage of 0.65,

supporting the claim that livelihood gains arise through multiple sufficient bundles (Ragin, 2009; Fiss, 2011; Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018). The configuration structure differs from HEP, suggesting that livelihoods and compliance share some enabling conditions but are not governed by identical causal architectures (Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018).

The first HSP pathway is a market-community-inclusion recipe in which formalisation quality, community embeddedness, and gender inclusion are core presences, while institutional support and mechanisation are not required to be core (Ragin, 2009; Fiss, 2011; Schneider and Wagemann, 2012). This solution is consistent with the claim that predictable formalisation experienced at the site level can stabilise earnings and local linkages when embeddedness and inclusion secure cooperation and broaden participation into value-added roles (Prescott *et al.*, 2022; Busia and Arthur-Holmes, 2024). The presence of GI as a core condition is theoretically significant because it positions gender inclusion as a productive condition in livelihood formation rather than as a residual social outcome. Typical cases include NG-018 and OG-033, which exhibit high membership in the configuration and support the interpretive reading (Fiss, 2011; Greckhamer *et al.*, 2018).

The second HSP pathway is a state-service-technology recipe in which institutional support and mechanisation are core requirements, whereas community embeddedness and gender inclusion are not (Ragin, 2009; Fiss, 2011; Schneider and Wagemann, 2012). This pathway indicates that livelihood stability can be achieved through credible service coverage and cleaner technology adoption even where community ties and inclusion are less developed, which is consistent with governance accounts that treat capability upgrading and institutional support as proximate mechanisms for stabilising production and earnings (Prescott *et al.*, 2022; Saridakis *et al.*, 2022). The result is interpreted as a sufficient empirical pattern, not as a normative claim that CE and GI are expendable in ASM development policy. Typical cases include NB-025 and PT-012, which support the state-service-technology interpretation (Fiss, 2011; Greckhamer *et al.*, 2018) (see Tables 10-13).

Analysis of negated outcomes

Separate modelling of negated outcomes indicates distinct causal structures for –HEP and –HSP, supporting causal asymmetry and rejecting the assumption that low performance is the mechanical inverse of high performance (Ragin, 2009; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). The principal –HEP configuration features the joint absence of institutional support and mechanisation as its core, indicating that weak oversight credibility coupled with low operational upgrading is sufficient for persistent environmental underperformance (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). This result shows that environmental failure is especially likely where sites lack both institutional

Table 10. fsQCA solutions for HEP and HSP

Solution	Core conditions	Peripheral / do-not-care conditions	Consistency	Raw coverage	Unique coverage	PRI	Typical cases
HEP-S1	FQ●, IS●, MECH●	CEO, GIO	0.87	0.42	0.23	0.74	ZG-014; OG-021
HEP-S2	IS●, CE●, GI●	MECH○	0.85	0.36	0.19	0.71	EL-009; PT-027
HSP-S1	FQ●, CE●, GI●	ISO, MECH○	0.86	0.39	0.21	0.73	NG-018; OG-033
HSP-S2	IS●, MECH●	CEO, GIO	0.84	0.34	0.18	0.70	NB-025; PT-012

Note(s): ● indicates core presence, present in both parsimonious and intermediate solutions. ○ denotes “do not care” in the reported solution

Table 11. fsQCA solutions for negated outcomes

Outcome	Solution	Core conditions	Peripheral / do-not-care conditions	Consistency	Raw coverage
¬HEP	¬HEP-N1	¬IS ●, ¬MECH ●	FQO, CEO, GIO	0.83	0.31
¬HSP	¬HSP-N1	¬CE ●, ¬GI ●	ISO, MECHO, FQO	0.82	0.29

Note(s): ~ denotes absence. ● indicates core absence, present in both parsimonious and intermediate solutions. ○ denotes “do not care”. The negated outcome solutions are interpreted as asymmetric sufficiency patterns rather than simple reversals of the positive-outcome models

Table 12. Heterogeneity checks, respondent vantage points and state clusters

Check	Summary finding	Implication for interpretation
Operator-only solutions	Same dominant solution families; lower coverage	Triangulation increases coverage without shifting the principal recipes
Community-only solutions	CE is more frequently core for both outcomes	Legitimacy-related mechanisms carry greater weight in community assessments
Regulator-only solutions	IS is more frequently core for both outcomes	Enforcement-facing assessments prioritise institutional credibility
State clusters, north versus south	MECH more often occurs in HEP-S1 in the north; CE more often occurs in HEP-S2 and HSP-S1 in the south	Context-conditioned equifinality across governance environments

Note(s): Heterogeneity checks assess whether the pooled solutions are driven by respondent group or state-cluster artefacts. They are treated as diagnostic checks rather than alternative main models

Table 13. Sensitivity and stability checks

Check	Specification	Result
Calibration sensitivity	±5 percentile full-in/out; ±0.05 crossover	All four main positive-outcome solutions retained; coverage change <0.03
Threshold tightening	Consistency ≥0.85; frequency ≥7	Solution composition unchanged
Influential-case assessment	Jackknife case deletion	Coverage change ≤0.04; no change to core conditions

Note(s): Sensitivity and stability diagnostics follow established guidance for set-theoretic applications

reinforcement and cleaner-practice capability; the absence of one condition alone is not presented as a universal failure mechanism.

The principal ¬HSP configuration features the joint absence of community embeddedness and gender inclusion as core, indicating that contested, exclusionary mine-community interfaces are sufficient for livelihood underperformance even where some formalisation artefacts exist (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). This finding is substantively important because it demonstrates that livelihoods can remain fragile when local legitimacy and inclusive participation are absent, even if licensing or technology-related elements are present in some form.

Operator-only estimations reproduce the main solution families with modestly lower coverage, indicating that pooling does not fabricate the principal recipes while still benefiting from multi-source triangulation (Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). Community-only estimates elevate CE as a core condition for both HEP and HSP, which is consistent with a

legitimacy-centred informational vantage point rather than contradicting the pooled findings (Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). Regulator-only estimations elevate IS as a core condition across outcomes, consistent with inspection and enforcement visibility as the primary informational basis for that respondent group (Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). State-cluster checks indicate that MECH is more frequently core in the northern cluster for HEP-S1, whereas CE is more frequently core in the southern cluster for HEP-S2 and HSP-S1, supporting context-conditioned equifinality across governance environments (Greckhamer *et al.*, 2018; Duşa, 2020).

These heterogeneity checks refine rather than weaken the pooled interpretation. They show that different respondent groups privilege different informational domains, while the main solution families remain substantively stable.

Sensitivity and stability checks

Calibration sensitivity retained all four main positive-outcome configurations, with marginal coverage shifts of less than 0.03, indicating membership-anchor stability (Schneider and Wagemann, 2012; Thiem, 2016; Duşa, 2020; Oana and Schneider, 2024). Raising the consistency threshold to 0.85 or the frequency threshold to 7 did not change solution composition, supporting solution persistence under stricter admissibility criteria (Schneider and Wagemann, 2012; Duşa, 2020). Jackknife case deletion shifted coverage by at most 0.04 without altering core conditions in the four principal solutions, limiting concerns that influential cases drive the findings (Thiem, 2016; Greckhamer *et al.*, 2018).

Across outcomes, the results indicate two families of sufficient pathways: one centred on governance-technology complementarity, FQ, IS, and MECH, and another centred on governance-community-inclusion complementarity, IS, CE, and GI. Livelihood outcomes further exhibit a pathway in which embeddedness and inclusion, together with the quality of formalisation, stabilise socio-economic performance (Ragin, 2009; Fiss, 2011; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). These patterns align with the theoretical claim that formalisation operates as a bundle whose performance effects depend on how oversight credibility, practice upgrading, legitimacy, and inclusion co-occur, rather than on licensing status alone (Prescott *et al.*, 2022; Arthur-Holmes and Ofori, 2024; Busia and Arthur-Holmes, 2024). The results, therefore, shift the interpretation from “formalisation works or fails” to a more precise claim: formalisation is associated with high performance only when it is assembled with complementary conditions in governance, technology, community, and inclusion. The configurations identify sufficient set-theoretic patterns observed within the sampled formalised sites, but they do not establish the temporal order through which institutional trust, technology adoption, community legitimacy, and gender inclusion emerge.

Discussion

The configurational results indicate that sustainability performance in formalised artisanal and small-scale mining (ASM) is shaped by the conjuncture of governance capacity, production capability, and local social ordering, rather than by any single lever of formalisation. This inference aligns with set-theoretic accounts of conjunctural causation, equifinality, and causal asymmetry, which treat outcomes as produced by multiple sufficient pathways, with causal ingredients that are not interchangeable across contexts (Fiss, 2011; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). The findings, therefore, move the formalisation debate beyond the binary question of whether licensing works, and instead specify the conditions under which formalisation becomes environmentally and socioeconomically productive. In this study, the intermediate solutions, when interpreted alongside parsimonious solutions to classify core and peripheral conditions, reveal two families of pathways for high environmental performance (HEP) and two for high socio-economic performance (HSP), with distinct causal structures for the negated outcomes

(Fiss, 2011; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). This interpretation is deliberately framed as set-theoretic sufficiency rather than definitive temporal causation because the study is cross-sectional and cannot establish the sequence through which formalisation quality, institutional trust, technology adoption, community embeddedness, and gender inclusion develop over time (Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018; Oana and Schneider, 2024).

HEP-S1, the governance-technology pathway (FQ ● IS ● MECH ●), implies that environmental gains are most likely where high formalisation quality is jointly present with trusted institutional support and demonstrable adoption of cleaner technology (Fiss, 2011; Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018). Interpreted substantively, the configuration suggests that formalisation is environmentally productive when legal authorisation and monitoring are experienced by operators as administratively workable and predictably enforced, and when these governance attributes are coupled with capability for cleaner processing, occupational health and safety practices, and waste or effluent controls (Fiss, 2011; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). This finding directly challenges accounts that treat licence acquisition as the main explanatory variable, because the pathway shows that environmental compliance depends on the co-presence of workable rules, credible institutions, and operational capability (Hilson and Maconachie, 2017; Hilson, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). The pathway is also consistent with sustainability-transition theory because cleaner technology adoption is not presented as a discrete artefact, but as part of a socio-technical alignment involving institutional support, monitoring credibility, finance, skills, and routine practice change (Geels, 2011; Prescott *et al.*, 2022; Keane *et al.*, 2023; Kohio *et al.*, 2024). The fact that CE and GI remain peripheral or “do-not-care” terms in HEP-S1 does not mean that community relations and inclusion lack importance; it means that this specific sufficiency route can achieve high environmental performance without those conditions appearing as consistent core requirements once FQ, IS, and MECH are jointly present (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017).

HEP-S2, the governance-community-inclusion pathway (IS ● CE ● GI ●), demonstrates an alternative sufficiency structure in which trusted institutional support combines with strong community embeddedness and gender inclusion to achieve high compliance even when mechanisation is not maximised (Fiss, 2011; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). This result positions local legitimacy and inclusion as functional governance complements that can stabilise compliance routines through social monitoring, grievance handling, and day-to-day cooperation at the mine community boundary (Prno and Slocombe, 2012; Bice, 2014; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). This shows that compliance is not simply a technical response to regulation; it is also shaped by local authority, trust, benefit distribution, and the social organisation of mining labour (Bebbington, 2015; Hilson, 2020; Beban and Banks, 2023; Adranyi *et al.*, 2024a, b). The configuration is theoretically important because it specifies a pathway to environmental performance that does not require technology to operate as a core ingredient, thereby supporting the view that compliance can be sustained through relational ordering and inclusion-oriented labour organisation when institutional trust and community consent are sufficiently strong (Fiss, 2011; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). In settings where cleaner technology diffusion is constrained by capital access, maintenance capacity, or uneven extension support, HEP-S2 indicates that institutional trust, community legitimacy, and women’s participation can provide an alternative route to environmental adherence (Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024).

For socio-economic outcomes, HSP-S1, the market-community-inclusion pathway (FQ ● CE ● GI ●), indicates that stable jobs, earnings, and local linkages are produced where formalisation is experienced as high quality, the site is embedded in local benefit-sharing and legitimate community relations, and women’s participation is substantively integrated into skilled, supervisory, or value-addition roles (Fiss, 2011; Schneider and Wagemann, 2012;

Misangyi *et al.*, 2017). This sufficiency logic challenges policy narratives that treat livelihood gains as an automatic consequence of licensing, because it implies that the livelihood function of formalisation depends on how legitimacy and inclusion convert legal status into continuity of operations, access to local labour, and stability of local commercial relations (Hilson and Maconachie, 2017; Hilson, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). This finding strengthens the gender argument by showing that gender inclusion is not merely an equity outcome to be measured after formalisation; it is part of the causal architecture through which formalised sites generate livelihood stability (Ofosu *et al.*, 2022; Baddianaah, 2023; Busia and Arthur-Holmes, 2024). The presence of GI as a core ingredient for HSP-S1 supports the interpretation that women's access to skilled work, training, leadership, and value-added roles can expand the local economic base of formalised ASM, where community embeddedness and formalisation quality are also present (Ofosu *et al.*, 2022; Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024).

HSP-S2, the state-service-technology pathway (IS ● MECH ●), provides a second route to strong livelihood outcomes, one grounded in institutional service credibility and cleaner technology adoption, while community embeddedness and gender inclusion are not core requirements in this sufficiency structure (Fiss, 2011; Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018). The mechanism interpretation is that livelihood stability can be generated through productivity and continuity effects when institutions supply credible support, training, dispute resolution, and predictable oversight, and when such support is paired with mechanisation and cleaner technology that reduce interruptions, accidents, and processing losses (Poppo and Zenger, 2002; Brammer and Walker, 2011; Cao and Lumineau, 2015; Sönnichsen and Clement, 2020). This finding complements the sustainability-transition reading by showing that cleaner technology can support livelihoods when embedded in institutional service systems rather than when promoted as an isolated equipment intervention (Geels, 2011; Prescott *et al.*, 2022; Kohio *et al.*, 2024). This pathway also implies that some sites may achieve livelihood stability through capabilities and state support, even as local legitimacy and inclusion continue to develop. However, this should be interpreted as a sufficient empirical pattern, not as a normative claim that community embeddedness or gender inclusion is indispensable in development policy (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017).

The analysis of negated outcomes indicates that low performance is not a mechanical inversion of high performance, thereby reinforcing the asymmetry principle of set-theoretic inference (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). The prominent –HEP structure centres on the joint absence of institutional support and cleaner technology, suggesting that weak oversight credibility combined with weak capability for cleaner processing yields a pathway to environmental failure that is not reducible to the absence of any one positive ingredient (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). This finding indicates that environmental underperformance is especially likely when sites lack both institutional reinforcement and practical capability for cleaner production, which is consistent with ASM studies showing that environmental improvement requires more than legal recognition or technical prescription alone (Hilson, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). The prominent –HSP structure centres on the joint absence of community embeddedness and gender inclusion, implying that livelihood failure can occur even when formalisation and technology are present if social legitimacy and inclusive participation are absent (Schneider and Wagemann, 2012; Misangyi *et al.*, 2017). This result reinforces the argument that formalisation can reproduce exclusion or uneven distribution of benefits when power, participation, and local legitimacy are not addressed at the mine-community interface (Bebbington, 2015; Beban and Banks, 2023; Adranyi *et al.*, 2024a, b). These results matter for policy design because they indicate that “fixing” one element, such as accelerating mechanisation, may not prevent failure if institutional credibility or community settlement is absent, and that livelihood fragility may persist when inclusion and legitimacy are treated as ancillary rather than constitutive (Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018; Busia and Arthur-Holmes, 2024).

Existing ASM studies show that formalisation frequently falters when policy assumes that licences, registration, and oversight automatically produce compliance or welfare gains (Hilson and Maconachie, 2017; Hilson, 2020; Prescott *et al.*, 2022; Arthur-Holmes and Ofosu, 2024). These findings indicate that the quality of formalisation becomes performance-relevant when it is assembled with trusted institutions, cleaner-practice capability, community legitimacy, and gender inclusion. This contribution extends configurational theory by demonstrating how a policy intervention can operate as a condition within alternative sufficiency bundles rather than as an independent treatment with uniform effects (Fiss, 2011; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). This study, therefore, advances ASM formalisation theory from a licence-centred account to a configuration-based account of implementation, capability, legitimacy, and inclusion.

Political ecology argues that extractive outcomes are shaped by authority, access, distribution, territorial control, and unequal exposure to risk (Bebbington, 2015; Beban and Banks, 2023; Adranyi *et al.*, 2024a, b). The fsQCA results operationalise these concerns by showing that community embeddedness and gender inclusion are not background context, but causal conditions that shape whether formalisation produces livelihood stability and environmental adherence. This is especially visible in HEP-S2 and HSP-S1, where CE and GI operate as core terms, and in –HSP, where their joint absence forms a pathway to socio-economic underperformance. The implication is that formalisation cannot be assessed only through state capacity or site-level productivity; it must also be assessed through the distributional and relational conditions under which mining communities recognise, contest, or co-produce compliance.

Sustainability-transition scholarship shows that technical change depends on alignment among technologies, institutions, markets, infrastructures, and user practices rather than on the diffusion of artefacts alone (Geels, 2011; Köhler *et al.*, 2019; Bofo and Arthur-Holmes, 2025). The governance-technology and state-service-technology pathways support this logic because MECH appears as a core condition only when paired with institutional support or formalisation quality. This finding qualifies technology-centred accounts of ASM improvement by showing that cleaner processing and safety routines are more likely to support performance when embedded in credible service systems, monitoring routines, and capability support (Prescott *et al.*, 2022; Keane *et al.*, 2023; Kohio *et al.*, 2024). In this respect, the study positions cleaner technology not as an autonomous driver, but as a governance-mediated condition within a wider transition bundle.

Recent ASM gender scholarship documents persistent barriers to women's access to land, finance, skills, leadership, safe work, and higher-value mining roles (Ofosu *et al.*, 2022; Baddianaah, 2023; Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024). The findings from this study add a configurational contribution by showing where gender inclusion enters the performance architecture: it is core in HEP-S2 and HSP-S1, and its absence combines with weak community embeddedness in –HSP. This suggests that inclusion can strengthen compliance and livelihood stability when it is connected to institutional trust and community legitimacy, rather than treated as a policy add-on (Ofosu *et al.*, 2022; Busia and Arthur-Holmes, 2024).

Methodologically, the study responds to best-practice expectations in configurational research by sequencing measurement validation before calibration, reporting necessity analysis with coverage diagnostics, and interpreting intermediate solutions alongside parsimonious solutions to classify core versus peripheral ingredients (Fiss, 2011; Schneider and Wagemann, 2012; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). The use of MICOM-based invariance assessment, which supports full invariance across respondent groups and state clusters, strengthens the basis for pooled calibration and pooled configurational inference, given the multi-source design and cross-state setting. The sensitivity and stability checks reported for calibration anchors, frequency and consistency thresholds, and case-deletion diagnostics align with guidance that set-theoretic results should be examined for

solution stability rather than treated as single-shot outputs (Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018; Pappas and Woodside, 2021; Oana and Schneider, 2024).

The configurations imply that “licensing plus inspection” should be treated as a governance platform whose performance depends on complementary mechanisms that vary by site constraints and local conditions (Fiss, 2011; Misangyi *et al.*, 2017; Greckhamer *et al.*, 2018). For sites aligned with HEP-S1, managerial priority should be to translate formalisation quality into operational routines by pairing procedural compliance with verified cleaner-processing capability, including consistent PPE use and waste or effluent controls, because the sufficiency logic suggests that governance credibility and technology capability jointly support high environmental performance (Brammer and Walker, 2011; Thomsen *et al.*, 2018; Prescott *et al.*, 2022). For sites aligned with HEP-S2, governance design should prioritise institutional trust, grievance settlement, benefit-sharing, and meaningful women’s participation, because these terms jointly support compliance even when technology intensity is moderate (Prno and Slocombe, 2012; Bice, 2014; Arthur-Holmes and Ofosu, 2024; Busia and Arthur-Holmes, 2024). This practical implication is more precise than a general call for formalisation because it specifies which bundles should be assembled under different site conditions.

For livelihood outcomes, HSP-S1 implies that formalisation programmes that ignore local legitimacy and inclusion may under-deliver on stability, even when licences exist and markets are accessible, because stable employment and earnings appear as products of locally embedded operational continuity combined with inclusive participation (Fiss, 2011; Misangyi *et al.*, 2017; Arthur-Holmes and Ofosu, 2024). HSP-S2 indicates that institutional service credibility, paired with cleaner technology, can deliver livelihood stability in some settings, supporting the value of coupling enforcement with capability support, such as training and equipment access, rather than relying on sanctions or paperwork compliance (Brammer and Walker, 2011; Sönnichsen and Clement, 2020; Prescott *et al.*, 2022). Across all pathways, the centrality of institutional support suggests that regulators and programme designers should prioritise predictability, dispute resolution, inspection fairness, and service delivery integrity as performance-producing institutional attributes, rather than merely administrative ideals (Hilson, 2020; Prescott *et al.*, 2022; Adranyi *et al.*, 2024a, b).

The study’s cross-sectional design limits temporal inference about sequencing, path dependence, and transition dynamics across renewals, technology upgrading, and evolving community relations (Schneider and Wagemann, 2012; Greckhamer *et al.*, 2018). Accordingly, the findings should be read as configurational sufficiency patterns observed within the sampled formalised sites, rather than as proof that the identified conditions always precede the outcomes. Future research could employ panel designs that track sites through formalisation stages and renewal cycles, enabling tests of whether specific conditions act as early-stage catalysts or late-stage stabilisers across different configurations (Furnari *et al.*, 2021; Pappas and Woodside, 2021). The multi-source design and administrative validation reduce reliance on single actor perceptions, but future work could extend external validation by using traceability data and longitudinal inspection histories, where available, thereby testing whether market discipline consolidates, substitutes for, or destabilises the governance-technology pathway over time (Brammer and Walker, 2011; Prescott *et al.*, 2022). Finally, further development of inclusion measurement could incorporate pay equity, task segmentation, leadership authority, and gender based safety exposure, thereby supporting more precise tests of how inclusion enters the causal architecture of environmental compliance and livelihood stability (Ofosu *et al.*, 2022; Busia and Arthur-Holmes, 2024).

Conclusion

This study develops a configurational account of how formalisation yields sustainability outcomes in artisanal and small scale mining by specifying sufficient-condition bundles for high environmental and socio-economic performance, rather than relying on additive net-

effect claims that obscure conjunctural causation and equifinality. In doing so, it addresses the central weakness in much ASM formalisation research: the tendency to treat legal recognition as an intervention whose effects can be inferred independently of implementation quality, institutional credibility, technological capability, community legitimacy, and gender inclusion. Empirically, the evidence indicates two equifinal pathways to high environmental performance with overall solution consistency of 0.86 and solution coverage of 0.68, and two equifinal pathways to high socio-economic performance with overall solution consistency of 0.84 and solution coverage of 0.65, with PRI values supporting directional adequacy under the stated thresholds and typical-case identifiers retained to substantiate the case-level interpretive claims.

Conceptually, the study re-specifies formalisation quality as a measurable, multi-attribute construct whose efficacy depends on its co-presence with credible institutional support, operational upgrading, community embeddedness, and gender inclusion, thereby shifting formalisation away from a binary legal-status framing toward implementation attributes empirically linked to performance. This reframing advances ASM formalisation theory by showing that licensing is not the explanatory endpoint; it is one condition within a broader architecture of governance, capability, legitimacy, and inclusion. In particular, the governance-technology pathway (FQ● IS● MECH●) constitutes a sufficient route to high environmental performance, as reflected in the configuration's consistency (0.87), raw coverage (0.42), unique coverage (0.23), and PRI (0.74), with typical cases such as ZG-014 and OG-021 demonstrating high membership in the recipe. This pathway supports a sustainability-transition interpretation because cleaner technology contributes to performance when it is embedded in credible institutional support and workable formalisation routines, rather than treated as an isolated equipment intervention.

The second high-environmental pathway (IS● CE● GI●) shows that trusted institutional support can secure compliance through locally legitimate arrangements and women's participation even where mechanisation is not core, consistent with the argument that relational governance and inclusion can function as enabling conditions for sustained adherence in resource governance settings. This finding strengthens the study's contribution by showing that environmental compliance is shaped by authority, local legitimacy, benefit distribution, participation, and trust, not solely by regulation or technology. The high socio-economic performance results both parallel and qualify these mechanisms: one pathway (FQ● CE● GI●) indicates that livelihood stability can be achieved where formalisation attributes cohere with community embeddedness and women's participation, while the alternative pathway (IS● MECH●) indicates that credible services combined with operational upgrading can stabilise livelihoods even when embeddedness and inclusion are not core. The distinction between these pathways shows that environmental compliance and livelihood stability are related but not governed by identical causal architectures, which justifies modelling the two outcomes separately rather than compressing them into a single sustainability score.

Methodologically, the study contributes a measurement-then-configuration workflow that aligns construct validation, transparent calibration, and solution diagnostics with contemporary expectations for replicability in set-theoretic research.

Calibration employs p90/p50/p10 anchors for Likert-type measures and rule-based anchors for practice-linked indicators, with sensitivity sweeps indicating that solution composition is stable under plausible anchor perturbations. The analysis also supports a sufficiency-centred interpretation: no single condition meets the 0.90 necessity threshold for high environmental or socio-economic performance, and the strongest candidates remain below it, consistent with the logic of causal complexity and the need to avoid necessity claims when they are not empirically warranted.

For practice and policy, the results yield a decision-oriented "recipe" logic that can be operationalised as assemblable intervention bundles rather than as a universal licensing model. For environmental outcomes, the governance-technology pathway implies that

inspection credibility should be paired with co-financing for cleaner processing circuits, PPE adoption, and effluent controls, while the governance-community-inclusion pathway implies that grievance systems, locally credible dispute resolution, benefit-sharing, and formalised women's roles can secure compliance even when equipment diffusion is slower. For livelihood outcomes, the market-community-inclusion pathway implies that strengthening site-level formalisation attributes alongside embedded local arrangements and women's progression into value-added roles can stabilise earnings, whereas the state-service-technology pathway implies that credible service coverage linked to upgrading can deliver gains even where embeddedness is not yet consolidated. The practical implication is therefore not that every site requires the same intervention package, but that policy actors should diagnose which complementary conditions are absent and assemble intervention bundles accordingly.

The study's limits also define tractable next steps. First, the cross-sectional design constrains inference on sequencing and path dependence, motivating panel studies that follow sites across renewals, inspection cycles, technology adoption, and community-relation trajectories. Second, integrating traceability, transaction records, and longitudinal inspection histories would permit stronger tests of whether market discipline consolidates, substitutes for, or destabilises specific governance bundles over time. Third, future inclusion measurement should incorporate pay equity, task segmentation, leadership authority, access to finance, and gender-based safety exposure, thereby testing more precisely how gender inclusion enters the causal architecture of environmental compliance and livelihood stability. Overall, this study demonstrates that formalisation in ASM is neither inherently transformative nor merely symbolic; its sustainability value depends on how legal recognition is assembled with institutional credibility, cleaner-practice capability, community legitimacy, and inclusion.

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