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ASSESSING ULTRA-MICRO DIGITAL PENSION FEASIBILITY FOR INFORMAL WORKERS: SIMULATION EVIDENCE WITH AI-ASSISTED CONTRIBUTIONS IN NTB INDONESIA

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Abstract
Informal workers dominate Indonesia's labour market but remain largely excluded from formal pension systems due to low and volatile incomes, raising concerns about old-age income security. The central question addressed is whether an ultra-micro digital pension scheme can generate meaningful retirement benefits for low-income informal workers and whether artificial intelligence (AI) can enhance contribution effectiveness under income uncertainty. A simulation-based framework is employed using official income statistics, combining deterministic and Monte Carlo simulations over a 25-year accumulation period and a 15-year payout phase. Three contribution designs are evaluated: a fixed ultra-micro nominal contribution, a flexible income-based contribution equal to 3% of earnings, and an income-based scheme augmented by an AI-assisted top-up mechanism. Fixed nominal contributions produce limited replacement rates of around 8%, while income-based contributions increase replacement rates to approximately 15%. The integration of AI-assisted contribution optimisation further raises replacement rates to about 19–20% and shifts the distribution of outcomes upward, improving downside protection under income volatility. Although the resulting benefits remain below conventional adequacy benchmarks, the findings demonstrate that ultra-micro digital pensions are financially feasible as complementary retirement instruments and that AI-enabled contribution mechanisms add measurable value in highly informal, low-income labour market settings.
Keywords: *digital pension; micro-pension; informal workers; financial inclusion; artificial intelligence*

INTRODUCTION

Informal employment continues to dominate labour markets in many developing economies, posing persistent challenges for the design of inclusive social protection systems. In Indonesia, data from the National Labour Force Survey (Sakernas) consistently show that approximately 57–59% of the employed population works in the informal sector, while only about 41–43% is engaged in formal employment. This structure mirrors broader international patterns, where informal workers constitute the majority of the labour force yet remain systematically excluded from contributory social security schemes, particularly old-age pensions.

The exclusion of informal workers from pension systems is not merely a coverage gap but a structural mismatch between product design and labour market realities. Conventional pension schemes are typically built around stable monthly wages, long-term employer–employee relationships, and regular payroll-based contributions. Such assumptions are fundamentally incompatible with the income profiles of informal workers, whose earnings are often low, irregular, and highly volatile. As a result, even when voluntary participation is formally permitted,

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effective access to pension schemes among informal workers remains extremely limited.

This challenge is especially salient in West Nusa Tenggara (NTB), a province characterised by a high prevalence of informal employment across agriculture, fisheries, small-scale trade, and informal services. Official statistics indicate that the average monthly net income of informal workers in NTB is approximately IDR 1.52 million. While this figure provides a useful aggregate benchmark, it conceals substantial heterogeneity across sectors and individuals. A significant segment of informal workers operates close to the national poverty line, facing tight liquidity constraints and limited capacity to commit to long-term savings. For these workers, mandatory or quasi-mandatory pension contributions calibrated to monthly wages are not only unattractive but often infeasible.

The international literature has long recognised that traditional pension systems perform poorly in contexts dominated by informality. Comparative studies and policy reviews emphasise that contributory schemes linked to formal employment leave the majority of informal workers uncovered, thereby exacerbating old-age poverty risks in developing countries. In response, a growing body of research and policy experimentation has focused on micro-pension arrangements—pension products designed with very small, flexible contributions that align more closely with the income patterns and saving capacities of informal workers. Evidence from countries such as Ghana suggests that informal workers are more likely to participate in pension saving when contributions are small, payment schedules are flexible, and institutional arrangements are simple and transparent.

At the same time, the rapid expansion of digital financial services has reshaped the feasibility frontier of pension inclusion. Over the past decade, Indonesia has experienced substantial growth in account ownership, electronic money usage, and digital payment infrastructure. Although gaps remain between income groups, digital finance has demonstrably lowered transaction costs and enabled small, high-frequency payments that were previously impractical under traditional banking models. In the context of pensions, digital platforms and mobile payment channels make it technically possible to collect ultra-small contributions on a daily or weekly basis, closely tied to actual cash flows rather than fixed monthly schedules.

Beyond digitalisation, recent advances in artificial intelligence (AI) introduce an additional layer of potential innovation in pension design. Robo-advisory systems and algorithmic financial tools have been shown to reduce advisory costs, automate portfolio management, and personalise financial recommendations. While most existing applications target middle- and high-income investors in advanced economies, emerging evidence suggests that AI adoption at the financial system level is associated with broader financial inclusion outcomes. Conceptually, AI may be particularly valuable in informal settings by helping to smooth behavioural biases, detect income patterns, and optimise contribution timing without imposing rigid obligations on participants.

Taken together, these developments raise a critical question for regions such as NTB: can an ultra-micro digital pension scheme—designed explicitly for low-income informal workers and supported by AI-assisted contribution mechanisms—generate meaningful old-age benefits despite low and volatile incomes? More

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specifically, does the integration of AI add measurable value beyond conventional flexible contribution schemes, or does it merely represent a technological embellishment with limited practical impact?

This study addresses these questions by evaluating the financial feasibility of an ultra-micro digital pension fund (Dana Pensiun/DAPEN) tailored to informal workers in NTB. Rather than examining individual behaviour through surveys, the analysis adopts a quantitative, simulation-based approach calibrated to official income statistics and macro-financial parameters. Multiple contribution designs are assessed, ranging from fixed ultra-micro nominal contributions to income-based schemes with AI-assisted top-up mechanisms. Performance is evaluated using indicators directly relevant to pension adequacy, including accumulated fund values, monthly pension benefits, and replacement rates relative to pre-retirement income.

By grounding the analysis in realistic income profiles and explicitly modelling income volatility through Monte Carlo simulations, this study contributes to the literature in three ways. First, it provides a quantitative assessment of how far ultra-micro pension schemes can go in improving old-age income security for the most vulnerable informal workers. Second, it offers empirical estimates of the magnitude by which AI-assisted contribution mechanisms can enhance pension outcomes, moving beyond abstract claims about the potential of AI in finance. Third, it generates policy-relevant insights for designing complementary pension pillars outside state-run systems, particularly in regions where informality remains structurally entrenched.

The persistence of informal employment poses a fundamental challenge to the architecture of pension systems in developing economies. A large body of literature has documented that contributory pension schemes rooted in formal labour contracts and payroll-based deductions systematically exclude informal workers, whose employment relationships are unregistered and whose incomes are often irregular and unobservable to social security institutions (Kudrna et al., 2025; OECD Publishing, 2024). International policy reviews emphasise that this exclusion is not incidental but structural, reflecting a deep mismatch between pension design and labour market realities in countries with high levels of informality.

Comparative studies on pension coverage in developing countries consistently show that informal workers remain largely uncovered by contributory pension systems. (Kudrna et al., 2025) identify the main barriers as the absence of formal employer–employee relationships, contribution floors that are too high relative to earnings, and administrative procedures that impose excessive compliance costs on small-scale and self-employed workers. (OECD Publishing, 2024) further highlights that pension reforms over recent decades have predominantly focused on improving sustainability and adequacy within the formal sector, often neglecting the informal majority. As a result, pension coverage rates in many low- and middle-income countries remain strikingly low despite sizeable informal labour forces.

In response to these structural limitations, the concept of micro-pensions has emerged as a policy and product innovation aimed at extending old-age protection to low-income and informal workers. Micro-pension schemes are characterised by very small contribution sizes, flexible payment schedules, and simplified

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administrative arrangements (De Jong & Van Dullemen, 2020). The underlying premise is that informal workers may be willing and able to save for retirement if contribution requirements are aligned with their income patterns and liquidity constraints. Empirical evidence supports this premise. Studies from Ghana demonstrate that informal workers are more likely to participate in pension saving when schemes allow irregular contributions, minimise transaction costs, and operate through transparent and trusted institutional mechanisms (Boyetey et al., 2021; Kumah et al., 2017). These findings are reinforced by behavioural studies showing that informal workers tend to exhibit strong present bias and high preference for liquidity, making rigid long-term financial commitments unattractive (Balliester Reis & Kamau, 2025; Sharma, 2025).

The effectiveness of micro-pension schemes, however, is closely tied to the infrastructure through which contributions are collected and managed. Traditional banking channels often entail transaction costs and minimum balance requirements that undermine the feasibility of very small, frequent contributions. The rapid expansion of digital financial services has therefore been identified as a critical enabler of pension inclusion. A growing empirical literature demonstrates that digital financial inclusion—driven by mobile money, electronic wallets, and digital payment systems—significantly improves access to formal financial services among low-income populations (Becha et al., 2025). Cross-country analyses further show that digital financial services reduce participation barriers, facilitate small-value transactions, and increase the likelihood that previously unbanked individuals engage with formal financial products (Niankara & Traoret, 2023; Xi & Wang, 2023).

In the context of pension provision, digital platforms enable the operationalisation of ultra-micro contributions that would be prohibitively costly under conventional systems. Evidence from the People's Pension Trust in Ghana illustrates how mobile money channels can be leveraged to collect daily or weekly pension contributions from informal workers, while maintaining accurate record-keeping and fund management (Arthur-Holmes & Agyemang-Duah, 2021). These experiences suggest that digitalisation is not merely a delivery mechanism but a structural component of viable pension solutions for informal economies.

More recently, advances in artificial intelligence (AI) have added a new dimension to discussions of pension design and financial inclusion. The literature on robo-advisors and AI-driven financial services highlights their potential to lower advisory costs, automate portfolio allocation, and personalise financial recommendations at scale (Liu, 2025). Systematic reviews of robo-advisory services indicate that algorithmic tools can replicate many functions of traditional financial advisors while operating at significantly lower cost, thereby expanding access to financial planning services beyond affluent client segments (Cardillo & Chiappini, 2024). Although most empirical studies focus on developed markets, emerging evidence suggests that AI adoption at the financial system level is positively associated with broader financial inclusion outcomes (Subramaniam et al., 2025).

From a behavioural perspective, AI-based tools may be particularly relevant in informal settings characterised by income volatility and limited financial literacy. By analysing historical income patterns, AI systems can identify periods of relative surplus and recommend or automatically implement additional contributions

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without imposing rigid obligations (Başar et al., 2025). Such mechanisms may help mitigate behavioural biases such as inertia and present bias, which have been widely documented among low-income households (Sharma, 2025). Importantly, the potential contribution of AI lies not in increasing mandatory contribution rates, but in improving the timing and allocation of contributions in a manner that remains compatible with participants' cash-flow constraints (Mutasa et al., 2024).

Despite growing interest in digital pensions and AI-enabled financial services, quantitative evidence on their effectiveness in informal, low-income contexts remains limited. Much of the existing literature relies on survey-based analyses of perceptions and intentions, or descriptive evaluations of pilot programmes (Balliester Reis & Kamau, 2025). Fewer studies explicitly quantify the magnitude of pension benefits that can realistically be generated under ultra-micro contribution schemes, particularly when income volatility is taken into account (De Jong & Van Dullemen, 2020). Moreover, claims regarding the added value of AI in pension design are often conceptual, lacking empirical benchmarks that distinguish meaningful performance gains from marginal improvements (Liu, 2025).

Against this backdrop, the present study adopts a simulation-based approach to evaluate the financial feasibility of an ultra-micro digital pension scheme tailored to informal workers in West Nusa Tenggara. By calibrating contribution scenarios to official income statistics and explicitly modelling income uncertainty, the analysis seeks to bridge the gap between conceptual discussions of inclusion and quantitative assessments of pension outcomes (Torm & Oehme, 2024). The integration of an AI-assisted top-up mechanism allows for a direct comparison between conventional flexible contribution schemes and designs that actively respond to income fluctuations (Cardillo & Chiappini, 2024; Subramaniam et al., 2025).

Conceptually, the framework underlying this study links three strands of literature: the structural exclusion of informal workers from formal pension systems, the role of digital financial inclusion in enabling micro-scale saving, and the potential of AI to optimise financial decisions under uncertainty (Mutasa et al., 2024). Within this framework, pension adequacy is assessed not in absolute terms but relative to realistic income benchmarks faced by informal workers. The key performance metrics—accumulated pension wealth, monthly pension benefits, and replacement rates—provide a transparent basis for evaluating whether ultra-micro digital pensions can meaningfully enhance old-age income security and whether AI contributes incremental value beyond flexible contribution design alone.

METHODS

This study employs a quantitative simulation-based framework to evaluate the financial feasibility of an ultra-micro digital pension scheme for informal workers in West Nusa Tenggara (NTB). The analysis focuses on pension wealth accumulation during the working life and benefit decumulation during retirement, under alternative contribution designs. The approach is forward-looking and evaluative rather than inferential, aiming to quantify pension outcomes generated by different scheme architectures under realistic income dynamics.

Let Y_t denote annual labour income in year t_1, where $t = 1, 2, \dots, T \; and \; T = 25$ represents the accumulation horizon from age 35 to 60. Income parameters are anchored to official statistics published by Statistics Indonesia (BPS), which report

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an average monthly net income of informal workers in NTB of IDR 1,522,644 in 2023. To capture a conservative and policy-relevant case, the representative worker in the simulations earns 50% of this average income. Thus, expected annual income is defined as:

$$\bar{Y} = 12\ x\ 760,000 = 9,120,000\ IDR$$

This income level lies slightly above the national poverty line and represents a vulnerable segment of informal workers with limited saving capacity.

All simulations assume zero initial pension wealth. Contributions are accumulated over $T = 25$ years and invested at a constant real rate of return r. During the accumulation phase, r is set at 6% per year, while during the payout phase a more conservative real return $r_p = 4\%$ is assumed. These values are consistent with recent monetary conditions in Indonesia, where nominal policy rates have ranged between 5.75–6.25% and inflation between 1.6–2.5%.

Four contribution scenarios are analysed. Scenario 0 serves as a baseline without pension participation, such that annual contributions satisfy:

$$C_t = 0\ \ \forall t.$$

Scenario 1 represents an ultra-micro nominal contribution scheme. Contributions are defined as a fixed nominal amount per working day. Given irregular work patterns and operational frictions, the annual contribution is calibrated directly as a constant:

$$C_t = \bar{C}1 = 150,000\ \ \forall t,$$

which corresponds to approximately 1.6% of annual income for the representative worke

Scenario 2 models a flexible micro-pension scheme based on a fixed proportion of income. Annual contributions are defined as:

$$C_t = \gamma Y_t,$$

where $\gamma = 0.03$. Under deterministic simulations, income is fixed at $Y_t = \bar{Y}$, yielding an average annual contribution of $\bar{C}_2 = 0.03 \times \bar{Y} = 273{,}600\ IDR$

Scenario 3 extends Scenario 2 by incorporating an AI-assisted top-up mechanism that responds to income fluctuations. The baseline contribution remains Y_t, but an additional contribution is triggered when income exceeds a threshold θt . The threshold is defined as:

$$\theta_t = X.\frac{1}{5}\sum_{k=t-5}^{t-1} Y_k,$$

where $\lambda = 1.2$ represents a 20% surplus relative to the moving average of income over the previous five years. The AI-assisted contribution rule is given by:

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$$C_t = \gamma Y_t + \alpha \max(Y_t - \theta t, 0),$$

where α ∈(0,1) is a scaling parameter calibrated such that the long-run average contribution rate approaches approximately 3.9% of income. For the representative worker, this implies an average annual contribution of approximately 356,000 IDR.

For each scenario, pension wealth accumulated at the end of the working life is computed using the standard future value formula:

$$FV_T = \sum_{t=1}^{T} C_t(1+r)^{T-t},$$

In the special case of constant annual contributions $C_t = C$, this expression simplifies to the future value of an ordinary annuity:

$$FV_T = \mathrm{C}\frac{(1+r)^T - 1}{\mathrm{r}}$$

Accumulated pension wealth is converted into retirement benefits over a payout horizon of N=15 years (ages 60–75). Annual pension benefits AAA are calculated using the annuity formula:

$$A = FV_T \frac{r_p}{1-(1+rp)^{-N}}$$

and monthly pension benefits are obtained as A/12

Pension adequacy is assessed using the replacement rate (RR), defined as:

$$RR = \frac{A/12}{\bar{Y}/12} = \frac{A}{\bar{Y}}$$

Two complementary simulation approaches are implemented. In the deterministic simulations, income is fixed at $Y_t = \bar{Y}$ for all t, allowing transparent comparison across contribution designs under stable income conditions.

To capture income uncertainty characteristic of informal employment, Monte Carlo simulations are conducted. Annual income Y_t is modelled as a lognormally distributed random variable:

$$\ln(Y_t) \sim N(\mu, \sigma^2)$$

with parameters calibrated such that $E[Y_t] = \bar{Y}$ and the coefficient of variation lies between 0.4 and 0.5. For each scenario involving income-based contributions (Scenarios 2 and 3), 10,000 income paths of length T=25 are simulated. For each path, contributions, accumulated pension wealth, retirement benefits, and replacement rates are computed using the equations above. The resulting empirical distributions are summarised using means, medians, and interquartile ranges.

This simulation framework enables a rigorous and reproducible assessment of whether ultra-micro digital pension schemes can generate meaningful retirement

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income for low-income informal workers, and quantifies the incremental contribution of AI-assisted mechanisms under realistic income volatility.

RESULTS AND DISCUSSION

The results are presented in two stages. First, deterministic simulations are reported to provide a transparent benchmark under stable income conditions. Second, Monte Carlo simulations are used to assess the robustness of pension outcomes under income volatility, which is characteristic of informal employment.

Under the deterministic framework, annual income is fixed at its expected level of IDR 9,120,000, corresponding to a monthly income of approximately IDR 760,000. Contributions are therefore constant within each scenario, allowing direct comparison of pension outcomes across contribution designs. Table 1 summarises the accumulated pension wealth at the end of the 25-year accumulation period, the resulting monthly pension benefits over a 15-year payout horizon, and the implied replacement rates.

Table 1. Deterministic Simulation Results

Scenario	Contribution design	Annual contribution (IDR)	Accumulated pension wealth, FVTFV_TFVT (IDR)	Monthly pension benefit (IDR)	Replacement rate (%)
0	No pension scheme	0	0	0	0.0
1	Ultra-micro nominal (≈ IDR 1,000/day)	150,000	≈ 8,230,000	≈ 61,700	≈ 8.1
2	3% of annual income	273,600	≈ 15,010,000	≈ 112,500	≈ 14.8
3	3% of income + AI top-up (≈ 3.9%)	355,680	≈ 19,510,000	≈ 146,300	≈ 19.2

Source: Primary data processed

The deterministic results indicate a clear ranking of contribution designs. The ultra-micro nominal scheme (Scenario 1) generates a positive but limited pension outcome, yielding an accumulated fund of approximately IDR 8.23 million and a monthly pension benefit of around IDR 61,700. This corresponds to a replacement rate of roughly 8.1% of pre-retirement income. While modest in absolute terms, this result demonstrates that even extremely small and irregular contributions can produce a non-zero pension benefit over a long accumulation horizon.

The income-based micro-pension scheme (Scenario 2) substantially improves pension outcomes. With contributions set at 3% of annual income, accumulated pension wealth increases to approximately IDR 15.01 million, generating a monthly pension benefit of about IDR 112,500 and a replacement rate close to 14.8%. Relative to Scenario 1, this represents an increase of nearly 80% in both accumulated wealth and monthly pension benefits.

The integration of the AI-assisted top-up mechanism (Scenario 3) further enhances pension performance. Under this design, accumulated pension wealth rises to approximately IDR 19.51 million, and monthly pension benefits increase to around IDR 146,300. The resulting replacement rate of about 19.2% reflects a gain of roughly 4.4 percentage points relative to the 3% income-based scheme.

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Importantly, this improvement is achieved with an average contribution rate of approximately 3.9% of income, rather than through a uniform increase in mandatory contributions.

To account for income volatility, Monte Carlo simulations are conducted for Scenarios 2 and 3, where contributions depend explicitly on realised income. Annual income follows a lognormal distribution with expected value IDR 9,120,000 and a coefficient of variation between 0.4 and 0.5. For each scenario, 10,000 income paths over the 25-year accumulation horizon are simulated, and pension outcomes are computed for each path. Table 2 reports the empirical distributions of accumulated pension wealth, monthly pension benefits, and replacement rates.

Table 2. Monte Carlo Simulation Results

Scenario	Statistic	Accumulated wealth (IDR)	Monthly pension benefit (IDR)	Replacement rate (%)
2: 3% income	Mean	≈ 15.01 million	≈ 112,500	≈ 14.8
	Median	≈ 14.90 million	≈ 111,700	≈ 14.7
	Q1	≈ 13.84 million	≈ 103,400	≈ 13.7
	Q3	≈ 16.06 million	≈ 120,600	≈ 15.8
3: 3% income + AI	Mean	≈ 19.70 million	≈ 148,900	≈ 19.4
	Median	≈ 19.39 million	≈ 146,800	≈ 19.1
	Q1	≈ 17.68 million	≈ 134,000	≈ 17.4
	Q3	≈ 21.40 million	≈ 162,200	≈ 21.1

Source: Primary data processed

The Monte Carlo results are consistent with, but more informative than, the deterministic benchmarks. Under Scenario 2, the distribution of replacement rates is centred around 14–15%, with a relatively narrow interquartile range of approximately 13.7–15.8%. This indicates that income volatility alone does not drastically alter expected pension outcomes when contributions scale proportionally with income, although downside risk remains for workers experiencing persistently low earnings.

Scenario 3 exhibits a clear upward shift in the distribution of pension outcomes. The mean replacement rate increases to approximately 19.4%, while the median replacement rate reaches about 19.1%. Notably, the lower quartile replacement rate under Scenario 3 (around 17.4%) exceeds the upper quartile replacement rate under Scenario 2 (around 15.8%). This distributional shift indicates that the AI-assisted top-up mechanism not only raises average pension outcomes but also improves downside protection by capturing surplus income in high-income years.

Across both deterministic and stochastic simulations, none of the scenarios achieves replacement rates commonly cited as adequate for maintaining pre-retirement living standards, often benchmarked at 30–40%. Nevertheless, the results demonstrate that ultra-micro digital pension schemes can generate meaningful and predictable retirement income supplements for low-income informal workers. Moreover, the AI-assisted contribution design delivers a quantifiable and economically meaningful improvement in pension outcomes relative to conventional flexible contribution schemes.

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The results of this study provide several important insights into the feasibility and limitations of ultra-micro digital pension schemes for informal workers in low-income contexts. First, the findings confirm a central argument in the pension and informality literature: while traditional contributory pension designs remain poorly suited to informal employment, appropriately calibrated micro-pension schemes can generate non-trivial retirement benefits even under severe income constraints. The deterministic and stochastic simulations show that ultra-small contributions accumulated consistently over long horizons yield positive pension wealth, reinforcing earlier empirical and conceptual arguments that contribution size alone should not be viewed as the primary barrier to pension participation among informal workers (De Jong & Van Dullemen, 2020; Torm & Oehme, 2024).

At the same time, the results underscore the inherent limitations of purely nominal ultra-micro contribution schemes. The replacement rate of approximately 8% generated under the fixed

nominal contribution design illustrates that, although such schemes are symbolically inclusive, their capacity to meaningfully protect old-age income is highly constrained. This finding aligns with international evidence showing that pension schemes relying solely on very small fixed contributions tend to produce benefits that are insufficient to substantially mitigate old-age poverty risks (OECD Publishing, 2024). From a policy perspective, this suggests that ultra-micro nominal schemes should not be promoted as standalone solutions but rather as entry-level instruments that familiarise informal workers with pension saving.

The income-based micro-pension design performs substantially better, yielding replacement rates close to 15% under both deterministic and Monte Carlo simulations. This improvement highlights the importance of proportional contribution mechanisms that scale automatically with earnings. By linking contributions directly to income, such schemes preserve affordability during low-income periods while capturing higher savings capacity when income rises. This result is consistent with empirical studies from developing economies that identify flexibility and proportionality as key determinants of sustained participation in voluntary pension schemes among informal workers (Boyetey et al., 2021; Kumah et al., 2017).

A central contribution of this study lies in quantifying the incremental value of AI-assisted contribution mechanisms. The simulation results demonstrate that integrating an AI-based top-up rule increases average replacement rates by approximately 4–5 percentage points relative to a standard income-based micro-pension scheme. Importantly, this improvement is not achieved through a uniform increase in mandatory contribution rates, but through selective capture of surplus income in high-income years. This finding provides empirical support for conceptual arguments that algorithmic tools can enhance financial outcomes by improving the timing and allocation of savings rather than by imposing stricter saving obligations (Aristei & Gallo, 2026; Cardillo & Chiappini, 2024).

The Monte Carlo simulations further reveal that the benefits of AI-assisted mechanisms extend beyond increases in average outcomes. The upward shift in the entire distribution of replacement rates indicates improved downside protection for participants facing income volatility. Notably, the lower quartile replacement rate under the AI-assisted scheme exceeds the upper quartile of the standard income-based scheme, suggesting that AI contributes to risk smoothing rather than merely

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amplifying gains for higher-income trajectories. This distributional effect is particularly relevant in informal labour markets, where income volatility is a defining feature and downside risk is often more consequential than upside potential (Mutasa et al., 2024).

Despite these improvements, the results also highlight the structural limits of micro-pensions in low-income settings. Even under the most favourable simulated scenario, replacement rates remain below commonly cited adequacy benchmarks of 30–40% of pre-retirement income. This finding reinforces a growing consensus in the literature that voluntary and micro-scale pension schemes cannot, on their own, deliver full income replacement for informal workers with persistently low earnings. Instead, their role is more appropriately conceptualised as a complementary pillar within a broader old-age protection framework that may include non-contributory social pensions, family transfers, and continued informal economic activity in old age.

From a theoretical standpoint, this study contributes to the literature by bridging three strands of research that are often examined in isolation: pension exclusion in informal labour markets, digital financial inclusion, and AI-enabled financial decision-making. By embedding AI directly into the contribution function and evaluating its impact through simulation, the analysis moves beyond abstract discussions of technological potential and provides concrete estimates of performance gains. This approach responds to calls in recent literature for more quantitative assessments of fintech and AI innovations in low-income and informal contexts (Liu, 2025; Subramaniam et al., 2025).

The findings also carry important policy implications. First, they suggest that regulatory frameworks for voluntary pension schemes should explicitly accommodate flexible and income-contingent contribution designs, rather than imposing rigid minimum contribution requirements. Second, the results indicate that digital infrastructure is not merely an operational convenience but a prerequisite for the viability of ultra-micro pensions, as it enables high-frequency, low-value transactions at minimal cost. Third, the quantifiable gains associated with AI-assisted mechanisms justify cautious experimentation with algorithmic tools in pension design, provided that transparency, data protection, and participant consent are adequately safeguarded.

Nevertheless, several limitations must be acknowledged. The analysis relies on simulated income paths calibrated to aggregate statistics, which may not fully capture sector-specific income dynamics or behavioural responses to pension incentives. The assumed rates of return, while grounded in recent macro-financial conditions, may differ from realised long-term investment performance. Moreover, the AI-assisted mechanism is modelled in a stylised manner and does not account for potential implementation challenges such as data availability, algorithmic bias, or user trust. These limitations suggest avenues for future research, including the integration of sector-level income data, sensitivity analysis under alternative return assumptions, and pilot-based evaluations of AI-enabled pension platforms.

Overall, the discussion reinforces the central conclusion that ultra-micro digital pension schemes, while inherently limited in their ability to deliver full income replacement, represent a financially feasible and policy-relevant instrument for expanding old-age protection among informal workers. The integration of AI adds measurable value by improving both average outcomes and downside

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protection under income volatility, thereby strengthening the case for technology-enabled, flexible pension designs in developing economies.

CONCLUSION

The simulation-based evidence confirms that ultra-micro digital pension schemes are financially viable for low-income informal workers, even under substantial income volatility. Very small and irregular contributions accumulated over long horizons generate positive pension wealth, although fixed nominal contribution designs produce limited replacement rates. Income-based contribution schemes perform substantially better, reflecting their closer alignment with the earnings profiles of informal workers. Integrating artificial intelligence into contribution design yields a measurable improvement in pension outcomes. AI-assisted top-up mechanisms increase replacement rates by approximately four to five percentage points relative to standard income-based schemes and shift the distribution of pension outcomes upward, enhancing downside protection under income uncertainty. These gains arise from improved timing and allocation of contributions rather than higher mandatory contribution rates. Despite these improvements, replacement rates remain below commonly cited adequacy benchmarks, highlighting the structural limits of voluntary micro-pension schemes in persistently low-income informal settings. Ultra-micro digital pensions therefore function most effectively as complementary instruments for old-age income support. Overall, the findings demonstrate that technology-enabled pension designs, particularly those incorporating AI-driven contribution optimisation, can meaningfully enhance retirement outcomes for informal workers while remaining compatible with severe liquidity constraints.

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