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Model Comparison, Uncertainty Quantification and Scenario-Based Projections of Nigeria Population Dynamics Using Classical and Fractional Growth Models

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Abstract

Precise population projections are indispensable for the effective formulation of sustainable development strategies, judicious resource allocation, and robust infrastructure development within burgeoning economies. Nigeria, as the most populous nation on the African continent, continues to exhibit substantial demographic expansion, consequently imposing escalating demands upon its healthcare, educational, housing, employment, and food systems. This investigation delves into Nigeria's population dynamics through the application of four distinct growth models: the Exponential, Logistic, Fractional Malthus, and Fractional Logistic models. Annual population data spanning the period 1991–2020 were meticulously calibrated employing a weighted parameter estimation methodology, wherein high weight was accorded to data derived from official census years. Model efficacy was rigorously assessed utilizing a suite of statistical criteria, including Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). Parametric uncertainty was quantified via bootstrap confidence intervals, while comprehensive sensitivity and scenario analyses were executed to explore divergent demographic trajectories. The Fractional Malthus model yielded the optimal fit to Nigeria historical data between 1991-2020, by achieving the lowest RMSE (3.0944) and MAPE (1.9542%) and projected a population of approximately 680million by 2060. The derived fractional order substantiates the presence of memory effects inherent in Nigeria's population growth process. Baseline projections forecast Nigeria's population to attain approximately 680 million by 2060, with plausible confidence bounds ranging from 604 to 727 million. This study introduces a unified fractional demographic modelling framework, which comprehensively integrates memory effects, uncertainty quantification, sensitivity analysis, and policy-oriented scenario planning, thereby constituting a significant extension of extant approaches to long-term population forecasting in developing economies. The findings demonstrate the effectiveness of fractional-order models for long-term demographic forecasting and policy planning. The results demonstrate that fractional-order models, particularly the Fractional Malthus model, provide a more reliable framework for long term population forecasting in Nigeria than classical growth models.

Keywords: Uncertainty Quantification, Scenario-Based Projections, Population Dynamics, Classical Growth Model, Fractional Growth Models

INTRODUCTION

Globally, population growth remains a pivotal factor influencing socioeconomic development. Accurate population projections are essential for governmental planning, resource distribution, urban expansion, labour market forecasting, healthcare provision, educational infrastructure development, and environmental sustainability. In fast-growing developing nations like Nigeria, precise demographic predictions are especially crucial as population growth directly impacts economic productivity, poverty reduction

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efforts, housing needs, transportation systems, food supply, and energy demand.

Nigeria currently holds the distinction of having the largest population in Africa and is projected to maintain its status as one of the world's fastest-growing African nations. According to the United Nations Department of Economic and Social Affairs (UN DESA, 2022), Nigeria's population will reach 375 million by 2050 and may reach 541 million by 2100. The UN also projects that Nigeria will become the third most populous country globally by 2050, overtaking the United States (UN DESA, 2015 & UNFPA Nigeria, 2024). This significant demographic increase presents both advantages and disadvantages. While a larger populace can offer an expanded workforce and broader consumer markets, it simultaneously intensifies demands on healthcare, education, public infrastructure, job creation, and environmental resources (UN DESA, 2015). Traditional population growth models, such as the exponential and logistic models, have been widely utilized for demographic predictions. The exponential model assumes unlimited growth, whereas the logistic model incorporates environmental constraints through a carrying capacity K, defined as the maximum population size an environment can sustain indefinitely. Unlike exponential growth, logistic growth includes density-dependent factors that slow growth as the population approaches K, producing the characteristic S-shaped curve. However, these conventional models often struggle to account for memory-dependent processes and inherited effects inherent in complex demographic systems.

Fractional calculus has emerged as a robust mathematical framework for modelling systems that exhibit memory and non-local interactions. Unlike standard integer-order differential equations, fractional differential equations consider past influences that shape current dynamics. Fractional-order models have been shown to capture "memory-dependent behaviour" in biological and population systems, where lower fractional orders introduce slower progression and reflect stronger memory effects (Singh et al., 2024). Similarly, recent work on fractal-fractional population resource models demonstrates that memory-dependent features and non-local dynamics are effectively captured by fractional operators with exponential decay kernels (Khan et al., 2025). Consequently, this approach has garnered increasing interest due to its enhanced ability to accurately describe real-world population processes.

Demographic developments are inherently cumulative, as factors like fertility rates, migration patterns, mortality improvements, educational attainment, healthcare investments, and socioeconomic shifts evolve gradually over time. Fractional calculus offers a natural mathematical framework for modelling hereditary effects through memory-dependent operators. By directly integrating past information into the governing equations, fractional models provide enhanced flexibility and realism compared to traditional integer-order formulations (Mohammed et al., 2024). This capability is particularly beneficial for rapidly developing nations like Nigeria, where demographic shifts unfold gradually and exhibit significant temporal persistence, and where fractal-fractional approaches have been noted to effectively capture memory phenomena in population dynamics under resource constraints (Khan et al., 2025).

Previous research has utilized classical mathematical and statistical models for population forecasting. For instance, Idemudia & Ojo (2023) investigated Nigeria's population growth using exponential and logistic models. They reported that while the exponential model accurately captured short-term growth, it tended to overstate long-term population size due to its assumption of unrestricted growth. Their findings indicated that the logistic model, by incorporating environmental and demographic constraints, offered more realistic long-term projections. However, the study acknowledged that both models might not fully account for persistent demographic memory effects related to fertility and migration patterns.

Similarly, Olusola (2021) examined demographic growth patterns in Sub-Saharan Africa using nonlinear regression and observed that many African population systems display strong persistence characteristics inadequately represented by ordinary differential equation models. The study contended that demographic behaviour in developing economies is shaped by long-term historical processes, including delayed fertility transitions, educational disparities, and urbanization pressures, thus necessitating more adaptable modelling frameworks. Akinyemi and Isiugo-Abanihe (2014) employed logistic growth analysis to study demographic transitions in Nigeria, concluding that models based on carrying capacity yielded more accurate long-term projections than exponential models. According to Dumitru et al. (2020), fractional-order models are especially valuable for biological and demographic systems because current system behaviour frequently relies on accumulated past states. Their work demonstrated that fractional models often achieve superior predictive performance in systems characterized by persistence and nonlinear interactions. In demographic forecasting, similar conclusions were drawn by Atangana. & Baleanu (2016), who asserted that fractional-order systems offer more precise representations of real-world dynamic phenomena by preserving information from previous states, rather than assuming purely instantaneous system evolution.

Recent advancements in computational demography have also promoted the use of machine learning and hybrid forecasting techniques. Traditional cohort-component models remain foundational, but their limitations in capturing nonlinearities and data sparsity have encouraged demographers to integrate data-driven approaches. Machine learning methods such as LSTM networks, random forests, and XGBoost are now increasingly applied to demographic forecasting because they can model complex interactions without strict parametric assumptions (Politis et al. 2025).

Hybrid architectures that combine deep learning with spatial-temporal modelling have shown particular promise for small-area population projections. For instance, Hikmat et al., (2025) proposed a dual-stream CNN-BiLSTM network with additive attention, which separately extracts spatial features and temporal dependencies to improve forecast accuracy across Australia, Japan, the US, and South Korea.

At the sub-national level, ensemble machine learning models have also gained traction. Wang et al., (2025) developed an SSA-XGBoost framework that integrates traditional census data with mobile phone signalling data. Their model achieved an R^2 of 0.9984 for mortality and migration forecasts in Hebei Province, demonstrating the value of multi-source data fusion for smart population management. Physics-informed approaches are another emerging direction. Tao (2025) introduced an LSTM-PINN hybrid that embeds policy-driven fertility functions within a deep learning structure, allowing age-structured projections from 2024 to 2054 while preserving demographic constraints.

Finally, graph-based methods are expanding the spatial flexibility of forecasts. Jeong et al., (2026) developed PopGNN, a Graph Neural Network model that produces population projections at both grid and administrative scales, addressing the long-standing challenge of scale-dependence in demographic modelling. Collectively, these developments indicate a clear shift toward hybrid and machine learning frameworks that complement classical demographic theory by improving predictive performance, uncertainty quantification, and adaptability to real-time data.

Traditional differential equation models assume that current population dynamics are solely influenced by present conditions. However, demographic processes are inherently cumulative, as factors like fertility behaviour, migration patterns, mortality improvements, educational attainment, health care investment, and socioeconomic shifts evolve gradually over time. Empirical demographic research shows that changes in mortality can affect fertility with lags of about 10 years, indicating that reproductive decisions are shaped by past survival experiences rather than only current rates (Angeles, 2010). Similarly, population momentum theory demonstrates that current growth is driven by the age structure inherited from previous decades, so that even after fertility falls to replacement level, populations continue to grow for generations (Laura & Thomas, 2020). Another key development in recent literature involves integrating uncertainty estimation and scenario analysis into population forecasting frameworks. In addition, Amurawaye (2026), applied classical and fractional order logistic models to project the population of Ogun state, Nigeria. The study shows a steady projected rise in future target years, demonstrating how fractional calculus handles memory and hereditary trait demographics better than standard inter-order models. World Bank (2024) report emphasized that long-term demographic projections should include confidence intervals and alternative growth scenarios because population systems are intrinsically uncertain and susceptible to changes in policy, migration, mortality, and fertility. These recommendations have encouraged researchers to move beyond singular deterministic forecasts towards probabilistic and scenario-based forecasting structures. Contemporary African demographic studies consistently highlight the continent's unprecedented population growth. According to the United Nations Economic Commission for Africa, Africa's population expanded from 283 million in 1960 to more than 1.5 billion in 2024, and is projected to reach 2.5 billion by 2050, with five African countries accounting for over half of global population growth in that period (Sinha & Getachew, 2024). The Pew Research Center (2024), analysing the UN World Population Prospects 2024, reports that Africa's population has grown more than sixfold since 1950 and is expected to reach 3.8 billion by 2100, even as growth slows in other regions. Similarly, the Institute for Security Studies' African Futures platform notes that Africa's population reached 1.55 billion in 2025 and is projected to double to 3 billion by 2061, driven by high fertility and population momentum, with the continent's working-age population set to exceed that of China and India combined by 2040 (ISS, 2025).

Recent projections by United Nations Department of Economic and Social Affairs, Population Division (2022) indicates that Nigeria is expected to become one of the world's most populous nations before the end of the century, underscoring the necessity of accurate forecasting methodologies. The continued reliance on oversimplified forecasting methods can lead to biased projections, with significant policy implications. Underestimation might result in shortages of schools, hospitals, housing, and employment opportunities, whereas overestimation could distort resource allocation and planning priorities. Consequently, there is a clear demand for forecasting approaches that better reflect Nigeria's transitional demographic reality. Although fractional-order models have demonstrated potential in other biological and dynamic systems, their application to Nigeria's population forecasting remains limited. This represents a methodological gap in existing literature. Therefore, this study develops a comparative forecasting framework for Nigeria, utilizing classical and fractional growth models, by integrating weighted regression techniques, official Nigerian census benchmarks, annual population estimates, fractional-order growth models, and comparative forecast evaluation criteria within a unified demographic forecasting framework.

METHODOLOGY

This study adopted a quantitative computational modelling approach to analyse and forecast Nigeria's population growth using both classical and fractional-order mathematical models. Annual population data for Nigeria covering the period 1991–2020 were obtained from the United Nations World Population Prospects database and supplemented with official Nigerian census benchmark figures for 1991 and 2006 (NPC, 2006).

Four demographic growth models were considered in the study, namely the Exponential Growth Model, Logistic Growth Model, Fractional Malthus Model, and Fractional Logistic Model. The classical models were included to represent conventional demographic forecasting approaches, while the fractional-order models were introduced to capture memory-dependent and nonlinear demographic dynamics.

The exponential growth model was represented by:

$$P(t) = P_0 e^{rt} \qquad (1)$$

The logistic growth model introduces environmental limitations through carrying capacity and expressed as:

$$P(t) = \frac{K}{1+\left(\frac{K-P_0}{P_0}\right)e^{-rt}} \qquad (2)$$

To account for demographic memory effects, the Fractional Malthus model is defined using the Mittag-Leffler function:

$$P(t) = P_0 E_{\propto}(rt^{\propto}) \qquad (3)$$

where $\propto$ denotes the fractional order presenting memory effects.

The fractional logistic model combines carrying capacity (K) and memory-dependent growth

$$P(t) = \frac{K}{1+\left(\frac{K-P_0}{P_0}\right)\frac{1}{E_{\propto}(rt^{\propto})}} \qquad (4)$$

$0 < \propto \leqslant 1$.

Model parameters were estimated using weighted nonlinear least-squares regression implemented in MATLAB. Greater weights were assigned to the official census years to enhance estimation stability and demographic credibility. The weighted objective function minimised the discrepancy between observed and predicted population values.

$$S(\theta) = \sum_{i=1}^{n} w_i \left[P_i - \widehat{P_i}(\theta)\right]^2 \qquad (5)$$

where w_i denote observation weights, P_i represent observed population values, $\widehat{P_i}(\theta)$ denotes model estimated values and θ is the parameter vector.

Model performance was evaluated using Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). Lower values of these criteria indicated better forecasting performance.

To assess parameter uncertainty and forecast reliability, bootstrap resampling with 500 replications was employed to generate 95% confidence intervals for the estimated parameters and future projections. Sensitivity analysis was further conducted by varying the estimated parameters by ±5% to examine the responsiveness of long-term forecasts to parameter changes.

All numerical simulations, optimisation procedures, confidence interval estimations, and graphical visualisations were carried out using MATLAB.

RESULTS AND DISCUSSION

From Table 1, the fractional orders, estimated at 0.9251 and 0.9409, signify considerable long-term memory effects within Nigeria's population system. These figures, nearing one, suggest that past trends in birth rates, death rates, population movement, and socioeconomic changes persistently impact current population patterns. Therefore, the progression of demographics cannot be accurately characterized as an immediate process; instead, it represents the accumulated outcomes from several preceding decades. To avoid early saturation effects during the historical fitting period, the carrying capacity was set at 3000 million during calibration. This figure was chosen because it significantly surpasses present and anticipated population figures reported by major international organizations like the United Nations and World Bank, yet it is large enough to model unrestricted growth throughout the calibration phase. As a result, K primarily serves as a stabilizing mathematical constant rather than a direct demographic forecast of Nigeria's eventual maximum population. The calculated carrying capacities (K) imply that significant population growth is still expected before saturation effects become predominant.

Table 1. Estimated Parameters of Population Models.

Model	**Growth Rate (r)**	**Carrying Capacity (K)**	**Fractional Order (α)**	**Remarks**
Exponential Model	0.031034	-	-	Classical unrestricted growth
Logistic Model	0.033918	1532.4779	-	Growth with carrying capacity
Fractional Malthus Model	0.037056	-	0.925096	Memory-dependent growth
Fractional Logistic Model	0.037270	3000	0.940889	Nonlinear fractional dynamics

Table 2. Model Performance Comparison.

Model	RMSE	MAPE (%)	AIC	BIC
Exponential Model	3.7312	2.3532	81.0034	82.4046
Logistic Model	3.5256	2.2771	79.6034	82.4057
Fractional Malthus Model	3.0944	1.9542	71.7748	74.5772
Fractional Logistic Model	3.1710	2.0115	75.2422	79.4458

Table 3. Bootstrap 95% Confidence Intervals.

Parameter	Lower Bound	Upper Bound
Growth Rate (r)	0.034477	0.048802
Fractional Order (α)	0.819634	0.958966

Table 4. Scenario-Based Population Projection (2021–2060) in millions.

Year	Low Scenario	Medium Scenario	High Scenario
2021	202.5	222.2	254.6
2030	254.3	288.1	329.8
2040	326.7	383.9	457.1
2050	419.1	510.9	633.1
2060	537.1	679.5	876.6

Table 5. 95% Bootstrap Confidence Intervals Population Projection (2021–2060) in millions.

Year	Low (95%)	Medium Scenario	Upper (95%)
2021	202.4	222.2	222.6
2030	279.7	288.1	296.1
2040	326.7	383.9	399.6
2050	468.5	510.9	539.2
2060	603.6	679.5	727.3

Table 6. Sensitivity Analysis Results for 2060 Projection.

Scenario	Projected Population (Millions)
Base Projection	679.5235
+5% Growth Rate	755.8455
-5% Growth Rate	611.1501
+5% Fractional Parameter	931.6274
-5% Fractional Parameter	509.3874

Table 7. Comparison with UN/world bank projection.

Year	Low (95%)	Medium Scenario	Upper (95%)	UN/World bank projection
2021	202.4	222.2	222.6	210-220
2030	279.7	288.1	296.1	260-280
2040	326.7	383.9	399.6	310-330
2050	468.5	510.9	539.2	360-400
2060	603.6	679.5	727.3	450-

Table 2 shows that among the various models tested, the Fractional Malthus model demonstrated the most superior overall performance. From a statistical perspective, it yielded the lowest error rates, indicating its excellent alignment with historical data. This outcome suggests that the Fractional Malthus specification offers the most accurate representation of Nigeria's past population trends. The robust efficacy of fractional models reinforces the increasing assertion that fractional differential equations are more adept at modelling real-world population systems, particularly in developing nations experiencing extended demographic shifts. Demographically, this implies that Nigeria's population development might be influenced not only by current growth factors but also by accumulated past demographic patterns, including persistent fertility rates, evolving mortality, migration inertia, and the momentum of its age structure. Conversely, the exponential model exhibited the weakest performance, signifying that Nigeria's population growth between 1991 and 2020 was not characterized by a consistently proportional rate. These findings suggest that more adaptable growth models are better suited to describe Nigeria's recent population trajectory than conventional exponential growth models.

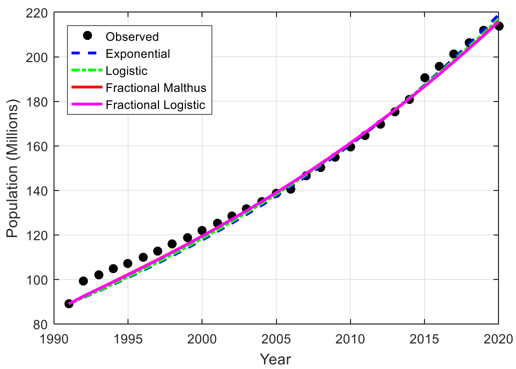

Fig 1: Model Fitting Comparison of Nigeria Population Models

In Figure1, the population fitting curves show close agreement between observed and predicted values. The exponential and logistic models adequately reproduce historical growth patterns; however, the fractional models align more closely with observations throughout the study period, particularly during years characterized by accelerated growth. The superior fit demonstrates the importance of incorporating memory effects into demographic modelling.

In Table 3, the constrained range of the confidence interval for the growth parameter suggests a consistent estimation of this parameter. Likewise, the fractional-order confidence interval consistently stays below one, thereby validating the statistical importance of population dynamics in Nigeria that are influenced by memory. Bootstrap inference offers considerable benefits in nonlinear fractional-order models, primarily because analytical distributions for parameters are typically not accessible, and assumptions of asymptotic normality might be untrustworthy. Resampling methods directly calculate the uncertainty of parameters using the observed data, without imposing limiting assumptions about their distribution.

The future of population trends is inherently uncertain because factors like birth rates, death rates, migration, healthcare advancements, urban development, educational levels, and economic growth can deviate from past patterns. To address this unpredictability, three distinct projection scenarios were created as revealed in Table 4 and Figure 2. These scenarios offer a realistic spectrum of potential demographic outcomes. Under optimal demographic conditions, Nigeria's population could reach approximately 877 million by 2060.

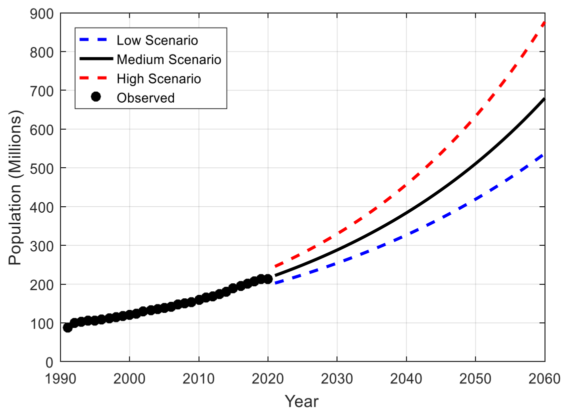

Fig 2: Scenario Analysis of Nigeria Population Forecast (2021-2060)

Conversely, a slower growth trajectory would result in about 537 million people. The most probable path, given current demographic conditions, is represented by the medium scenario, forecasting around 680 million. This medium scenario is the baseline prediction derived directly from the calibrated fractional model using estimated parameters. The low-growth scenario posits a 5% reduction in both the growth rate and the fractional-order parameter, reflecting possible demographic shifts such as decreasing fertility, later marriages, improved female education, and increased adoption of family planning. In contrast, the high-growth scenario assumes a 5% increase in both parameters, indicative of sustained high fertility, better child survival rates, enhanced healthcare, and accelerated population momentum. The choice of a ±5% perturbation level was made because it allows for a credible demographic variation without introducing unrealistic parameter distortions that might destabilize the model. Similar perturbation magnitudes are commonly used in sensitivity and scenario analyses within population modelling studies. In the high-growth scenario, Nigeria's population could exceed roughly 876.6 million by 2060. While this is not the most likely outcome, it demonstrates the significant implications of persistent high fertility, lower mortality, and continued population momentum. Such a demographic path would lead to a substantial increase in demand for housing, education, healthcare, employment, energy, and food. Therefore, this scenario serves as a crucial planning benchmark for policymakers by highlighting the upper limits of plausible demographic developments.

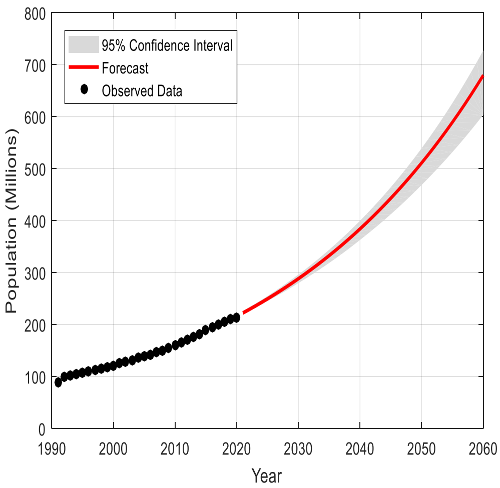

Fig 3: Nigeria Population Forecast (2021-2060) with Bootstrap-Based 95% CI.

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The confidence intervals widen progressively over time, reflecting increasing forecasting uncertainty as the prediction horizon extends. Nevertheless, the intervals remain sufficiently constrained to support meaningful demographic planning, Table 5 and Figure 3. By 2060, Nigeria's population is expected to lie between approximately 604 and 727 million under the estimated uncertainty range.

Table 6 reveals that the sensitivity results demonstrate that long-term forecasts are considerably more responsive to changes in the fractional-order parameter than to comparable changes in the intrinsic growth rate. While a ±5% variation in the growth rate altered the 2060 projection by approximately ±10%, an equivalent perturbation of the fractional parameter produced changes exceeding ±35%. This finding highlights the dominant role of demographic memory in shaping future population trajectories. Consequently, policies influencing long-term fertility behaviour, educational attainment, reproductive health outcomes, and generational demographic transitions may exert greater long-run effects than short-term population control measures.

The medium forecast obtained from the Fractional Malthus model projects a Nigerian population of approximately 288 million in 2030, 384 million in 2040, 511 million in 2050, and 680 million in 2060 as shown in table 7. These estimates are broadly consistent with projections reported by the United Nations World Population Prospects and World Bank demographic assessments, which anticipate continued rapid population growth throughout the twenty-first century. The present forecasts generally lie within the uncertainty ranges reported by international agencies, although the fractional model predicts slightly higher long-term values due to the incorporation of demographic memory effects. This agreement provides additional validation for the proposed modelling framework while highlighting the potential influence of persistent fertility and population momentum on future demographic expansion.

CONCLUSION

This study validated a fractional-order framework for forecasting Nigeria's population using historical demographic data from 1991 to 2020. The results demonstrate that incorporating memory effects through fractional calculus provides a more realistic representation of Nigeria's demographic trajectory than traditional integer-order models. Among the four models tested, the Fractional Malthus model achieved the best fit, with the lowest RMSE, MAPE, AIC, and BIC values, indicating its superior ability to capture the cumulative nature of demographic change.

The projections suggest that Nigeria's population will continue to grow rapidly over the next four decades, with the medium scenario estimating approximately 288 million by 2030, 384 million by 2040, 511 million by 2050, and 680 million by 2060. These figures are broadly consistent with UN and World Bank projections, though slightly higher in the long term due to the explicit inclusion of demographic memory.

From a policy perspective, the findings underscore the urgency of aligning national development planning with realistic population trajectories. The high sensitivity of long-term forecasts to the fractional-order parameter suggests that interventions targeting fertility behaviour, education, reproductive health, and labour market adaptation will have outsized effects over time. Expanding educational infrastructure, strengthening maternal and child health services, promoting family planning, and investing in job creation will be critical to harnessing Nigeria's growing population as a demographic dividend rather than a source of strain on resources.

This study offers four primary contributions to demographic forecasting studies. Firstly, it introduces fractional-order population models to analyse Nigerian population trends, thereby capturing long-term demographic patterns often overlooked by conventional growth models. Secondly, it combines weighted calibration, based on official census data, with annual United Nations population estimates to enhance parameter reliability. Thirdly, it includes bootstrap uncertainty quantification and sensitivity analysis to assess the robustness of forecasts. Lastly, scenario-based projections offer policymakers practical demographic trajectories for strategic planning. Together, these contributions establish a thorough population forecasting framework that provides enhanced adaptability and predictive realism compared to conventional integer-order methodologies.

LIMITATIONS AND FUTURE RESEARCH

Despite its contributions, this study has these limitations. The models used are aggregate and do not incorporate age-structure or sex-structure, which are central to cohort-component projections and to understanding dependency ratios. Moreso, migration was not modeled explicitly, even though internal and international migrations are increasingly important drivers of Nigeria's population distribution.

Future research can extend the framework in these directions (i) integrating fractional operators into age-structured models to capture both memory and demographic composition (ii) coupling fractional models with scenario-based assumptions on fertility decline, education, and migration policy. Doing so would provide policymakers with richer tools for anticipating the social and economic implications of Nigeria's demographic transition.

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