

Morbidity-Based Forecasting Improves Accuracy of Malaria Commodity Quantification in Zambia: A Comparative Analysis of Routine Program Data

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How to cite this paper: Kapobe, L. M., Mufwambi, W., Makowane, S., Samudata, R., Mbuzi, C., Neene, V., & Mudenda, S. (2026). Morbidity-Based Forecasting Improves Accuracy of Malaria Commodity Quantification in Zambia: A Comparative Analysis of Routine Program Data. *Open Journal of Business and Management*, 14, 1789-1808.

<https://doi.org/10.4236/ojbm.2026.144098>

Received: April 28, 2026

Accepted: June 28, 2026

Published: July 1, 2026

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Abstract

Background: Accurate forecasting of malaria commodities is essential to ensure an uninterrupted supply and effective disease control in endemic settings such in Zambia. In many low- and middle-income countries, consumption-based forecasting remains the standard approach, despite its inability to capture seasonality, trends and fluctuations. This study compared the accuracy of morbidity-based and consumption-based forecasting approaches for malaria commodities in Zambia. **Methods:** A comparative retrospective cross-sectional study was conducted using longitudinal national data from 2022 to 2025. Malaria morbidity data from the health management Information system (HMIS) and consumption records from the electronic logistics management information system (eLMIS) for key malaria commodities, artemether-lumefantrine, and malaria rapid diagnostic tests (mRDTs) were extracted and analysed. National forecast figures for 2022 to 2025 for morbidity and consumption-based methods were evaluated using mean absolute error (MAE) and the mean error (ME). Statistical significance testing was performed using the Wilcoxon signed rank tests and Diebold-Mariano tests to ascertain the statistical significance of the forecast performance of the morbidity forecast method against the consumption forecast method. **Results:** Morbidity-based forecasting consistently outperformed consumption-based methods for all commodities. The morbidity-based approach achieved substantial reductions in forecast error, with improvements ranging from approximately 35.95% to 75.85%. These dif-

ferences were statistically significant ($p < 0.05$) across all tests. In contrast, consumption-based forecasts systematically underestimated demand, particularly during periods affected by stockouts, supply constraints and seasonal case peaks. Despite its favorable performance, morbidity-based forecasting exhibited moderate error levels, indicating opportunities for further refinement. **Conclusion:** Morbidity-based forecasting provides a more accurate and epidemiologically aligned approach to malaria commodity forecasting than consumption-based methods in Zambia. Transitioning to morbidity-driven forecasting could improve supply chain efficiency, reduce stockouts, and enhance malaria treatment outcomes. Future research should focus on integrating environmental and seasonal variables and developing hybrid forecasting models that further improve predictive accuracy.

Keywords

Malaria, Forecasting, Morbidity-Based Quantification, Supply Chain, Antimalarial Commodities, Artemether-Lumefantrine, Rapid Diagnostic Tests, Zambia

1. Introduction

Malaria remains a major global health problem that is significantly impacting populations worldwide with the World Health Organization reporting 247 million cases in 2021 (Ippolito et al., 2025). Despite progress in malaria control through vector interventions and drug access improvements, Zambia remains a high-burden setting where supply chain inefficiencies undermine treatment outcomes (Chewe, 2025). Contemporary supply chain literature identifies demand signal distortion as a critical barrier where consumption data distorted by stockouts and procurement constraints mask true epidemiological demand, leading to systematic over forecasting and inventory misalignment (Kamere et al., 2023; Makowane et al., 2026; Mbuzy et al., 2026). This study addresses this gap by comparing epidemiologically grounded (morbidity-based) versus procurement-distorted (consumption-based) forecasting approaches, anchoring the analysis in established operations management theory rather than reiterating malaria epidemiology.

Supply chain management is crucial in resource-constrained settings, such as Zambia, where maintaining adequate inventory levels of antimalarial medicines and rapid diagnostics test at health facilities is challenging because of inadequate commodity forecasting approaches (Ippolito et al., 2022). Consequently, antimalarial stockouts mean that patients travelling long distances for medication may remain untreated. This increases the risk of severe complications or death from malaria (Chimombe et al., 2023). Although this poses a significant challenge to malaria control in Zambia (Ippolito et al., 2025), a large-scale trial in 439 health facilities across 24 districts showed a significant decline in stockouts for first-line paediatric antimalarials, dropping from 47.9% to 13.3%, with stockout days per

quarter reducing from 27 to 5 with more direct distribution (Vledder et al., 2019).

The surge in malaria during specific seasons such as the wet season is a significant challenge to populations and often leads to a shortage of antimalarial medications, thereby undermining malaria control efforts (Ippolito et al., 2025). A five-year study at a northern Zambian hospital confirmed that excess malaria mortality was directly associated with pharmacy and blood bank stockouts (Kabuya et al., 2024). Factors contributing to stockouts in Zambia include weaknesses in medical procurement, supply chain management, health infrastructure and human resource management (Obeagu et al., 2026). However, studies show that optimisation-based inventory policies using actual data and validated simulation models outperform base-stock policies in reducing stockouts of life-saving medicines in Zambia (Gallien et al., 2021).

This study is guided by an integrated theoretical framework that combines Demand Forecasting Theory, Supply Chain Resilience Theory, and the Health Systems Strengthening Framework, while drawing on the concepts of the bullwhip effect, information asymmetry, and decision support systems in healthcare procurement. Demand Forecasting Theory posits that morbidity-based forecasting provides a more accurate representation of true demand by using epidemiological data rather than historical consumption, which may be distorted by stockouts and procurement constraints. This addresses demand signal distortion and reduces the bullwhip effect, whereby small inaccuracies in demand estimation are amplified throughout the supply chain. Supply Chain Resilience Theory emphasizes that accurate and timely forecasts improve information visibility, reduce uncertainty, and enhance the responsiveness of procurement and distribution systems. The Health Systems Strengthening Framework highlights reliable access to essential medicines as a core component of effective service delivery and commodity security.

Within this framework, the forecasting approach (morbidity-based versus consumption-based) serves as the independent variable, while demand signal fidelity, information quality, uncertainty reduction, and supply chain responsiveness act as mediating mechanisms. These mechanisms influence forecast accuracy, inventory management, and procurement decision-making, ultimately leading to reduced stockouts and wastage, improved commodity security, better access to malaria diagnosis and treatment, and reduced malaria morbidity and mortality. By situating morbidity-based forecasting within these complementary theoretical perspectives, the study advances both forecasting methodology and supply chain theory and provides actionable evidence for strengthening pharmaceutical procurement and health systems in resource-constrained African settings.

2. Materials and Methods

2.1. Study Design

This study employed a retrospective comparative time-series analysis design. The unit of analysis was monthly commodity-level observations ($n = 47$ months per

commodity per method). The analysis evaluated the predictive accuracy of two forecasting methodologies using historical national forecasts from quantification reports for January 2022–November 2025, comparing forecasted versus actual monthly consumption for five malaria commodities. The retrospective design was selected for its efficiency in systematically analyzing existing operational data without the need for new data collection from study participants (Ippolito et al., 2025). The retrospective design reduced costs and time while maintaining methodological rigor (Ippolito et al., 2025).

2.2. Study Site

This study included all health facilities in Zambia, leveraging national-level aggregated data, and Zambia's diverse epidemiological landscape. The diverse landscape provided the capture of varying malaria transmission intensities across different regions. This provided a robust setting for evaluating the generalisability of forecasting methods (Das et al., 2025). The inclusion of all facilities ensures a comprehensive representation of the health system thereby capturing variations in service delivery, commodity consumption and morbidity patterns (Kabuya et al., 2024).

2.3. Study Population

Five selected malaria commodities representing Zambia's essential antimalarial treatment and diagnostic function were included in the study population. These comprised four distinct artemether-lumefantrine (AL) tablet dosage formulations: AL 6-tablet, AL 12-tablet, AL 18-tablet and AL 24-tablet formulations, along with malaria rapid diagnostic tests (mRDTs) for parasitological confirmation. The selection of these specific commodities was based on their role as Zambia's primary antimalarial treatment options and the availability of complete historical quantification data throughout all four study periods (Wang et al., 2025).

2.4. Sample Size Estimation and Sampling Techniques

Given the use of aggregated national-level data, this study did not involve traditional sampling techniques. Instead, data for the entire population (total enumeration) of health facilities in Zambia were included in the analysis for each reporting period (Imam et al., 2021). This approach maximised the statistical power of the study and ensured that the findings were representative of the entire country.

2.5. Instruments for Data Collection

Morbidity-based forecasts and Consumption based were extracted from national quantification reports compiled by Zambia's National Malaria Elimination Programme (NMEP). The Morbidity-based forecasts assumptions are based on HMIS data (monthly case-count observations) while Consumption-based forecasts were derived from assumptions based on logistics data from the electronic Management information system (eLMIS) and data from central warehouse Management

System (WMS) and the Quantification Analytics Tool (QAT). Both forecast series covered a 12-month forecast were updated monthly. For validation, consumption-based forecasts were reconstructed from raw eLMIS data and compared with reported forecast values to confirm data integrity. For clarity, morbidity-based forecasts were extracted directly from the National Malaria Elimination Programme (NMEP) quantification reports compiled from HMIS monthly case-count data, with 12-month forward forecasts updated monthly from January 2022 through November 2025. Consumption-based forecasts were similarly extracted from these reports but derived from historical logistics data (eLMIS, WMS, and QAT). Both methods generated prospective monthly forecasts using the same update frequency and forecast horizon. These data depositories are central repositories for facility logistics data (Sylvain et al., 2025).

2.6. Procedure for Data Collection

This study analyzed malaria commodity data in Zambia by decomposing national reconciliation tables. These reconciliation tables contained eLMIS Metabase records for facility-level consumption and HMIS for malaria cases for the study period. Because facility level consumption represented number of diagnosed cases, morbidity data were used as the forecasting comparator. Using a rigorous four-step protocol, a modified service provision assessment questionnaire and supporting data collection instruments were designed and used to systematically gather commodity data for five commodities across four quantification cycles (2022–2025) (Mulissa et al., 2020). A comprehensive validation through cross-verification with eLMIS databases and HMIS database records was conducted. In addition, documentation of discrepancies, assessment of missing data and confirmation of actual facility commodity consumption were conducted to ensure validated findings. The data were then organized into standardised spreadsheets for statistical analysis.

2.7. Data Analysis

To compare forecasting methodologies, the dataset comprised monthly time series observations for five malaria commodities (ACT 6, ACT 12, ACT 18, ACT 24, and mRDT) spanning 47 months from January 2022 to November 2025 ($n = 47$) per commodity per forecasting method (Penubaka et al., 2025). Three distinct data sources were integrated, actual facility consumption data from the electronic Logistics Management Information System (eLMIS), consumption-based forecasts derived from historical logistics patterns and morbidity-based forecasts generated from health service utilisation data (Wang et al., 2022). For each commodity and forecasting method combination, two primary accuracy metrics were calculated, these included the mean absolute error (MAE) and forecast error (Error difference or bias indicator). Positive mean error values indicate systematic overestimation (forecast > actual), while negative values indicate systematic underestimation (forecast < actual).

The dataset was stratified by commodity to enable commodity-specific com-

parisons, recognising that high-volume products (mRDT, ACT 24) exhibit different error patterns than lower-volume products (ACT 6, ACT 12, ACT 18). A missing value assessment was used to confirm data completeness across all observations with no imputation required. Hypothesis testing employed a multi-tiered statistical approach to compare forecasting methodologies and evaluate temporal trends.

Wilcoxon signed-rank tests compared paired monthly forecast errors for each commodity across all 47 months. The monthly loss series was the paired difference in absolute forecast errors (Morbidity-based MAE per month minus Consumption-based MAE per month), with a two-tailed test at $\alpha = 0.05$ assessing whether the median absolute error difference was significantly different from zero. Effect size was reported as Cohen's *d*.

Diebold-Mariano tests evaluated directional accuracy, comparing the Mean absolute error (MAE) of monthly forecasts for morbidity-based versus consumption-based. The test compared the monthly mean absolute error (MAE) series for morbidity-based vs. consumption-based forecasts for each commodity across the full 47-month observation period, using a 12-month forecast horizon and assessing directional accuracy of forecast error reduction (Tapio, 2025).

These tests, which operate based on rank-ordered data rather than assuming normality, are particularly suitable when data violate parametric test assumptions. Diebold-Mariano directional accuracy tests evaluated whether one forecasting method systematically predicted consumption trends more accurately than the alternative, providing clinically relevant signal-detection metrics beyond traditional accuracy measures (Harvey et al., 2024).

Actual consumption was defined as the quantity of commodities issued to dispensing points within health facilities and to community health workers within facility catchment areas as recorded in eLMIS for each calendar month. Because recorded consumption is constrained during months when stock is unavailable (i.e., zero consumption may reflect stockout rather than zero demand), we documented all stockout months separately. To address this limitation, we conducted a sensitivity analysis excluding stockout-affected months results remained consistent (data not shown), justifying the use of recorded consumption as the reference outcome.

Health facility consumption data were compared with morbidity data as a cross-validation approach to enhance forecasting accuracy. In the context of Zambia's policy mandating diagnosis-based prescription, both methodologies were inherently linked to the burden of laboratory-confirmed malaria cases. In principle, antimalarial consumption volumes were expected to correspond directly with confirmed case numbers. However, a notable disparity was frequently observed in practice, requiring reconciliation of underlying systemic factors.

This variance was largely attributed to presumptive treatment practices, stockouts that constrained recorded consumption despite high morbidity, and inconsistencies in reporting within the HMIS. Through the triangulation of these datasets, it was possible to differentiate actual changes in disease prevalence from

inefficiencies in the supply chain or deviations from established treatment guidelines.

Seasonal indicators were derived from Zambia's epidemiological calendar (wet season which is from November to April and dry season from May to October) and integrated into the morbidity-based forecasts through stratified analysis. This allowed evaluation of whether morbidity-based forecasting maintains accuracy advantage across seasonal demand variations.

2.8. Ethical Approval

Ethical approval to conduct the study was granted by the University of Zambia Health Sciences Research Ethics Committee (UNZAHSREC) [Protocol ID Number 2023270453] and the Zambia National Health Research Authority (NHRA) [NHRA-2777/08/10/2025] in compliance with national and institutional guidelines. This study utilised secondary data and adhered to rigorous ethical standards concerning data governance, institutional oversight and policy relevance. All datasets were handled in accordance with established data protection protocols. These included secure storage, controlled access and anonymisation as applicable. No personal identifiable information was used or disclosed. Data sharing followed the principles of Findable, Accessible, Interoperable, and Reusable (FAIR) and any shared datasets were de-identified and distributed under appropriate data use agreements. Publications complied with open science and institutional policies to promote transparency, reproducibility, and equitable access to knowledge.

3. Results

This section presents a comprehensive evaluation of forecasting accuracy by comparing morbidity-based and consumption-based methods for predicting malaria commodity demand across five product categories over a 47-month period.

Table 1 summarizes the forecast accuracy of the morbidity-based forecasting approach for five malaria commodities over 47 monthly observations. The mean absolute error (MAE) varied considerably across commodities, ranging from 2,431 packs for ACT 18 to 64,170 kits for malaria rapid diagnostic tests (mRDTs), indicating differences in forecasting precision by product type and demand volume. Among the artemisinin-based combination therapy (ACT) formulations, ACT 18 demonstrated the highest accuracy, followed by ACT 12 and ACT 6, while ACT 24 showed comparatively larger forecasting errors. The positive mean errors observed for ACT 12, ACT 18, ACT 24, and mRDTs suggest a tendency toward overestimation, whereas the negative mean error for ACT 6 indicates slight underestimation.

Table 1. Accuracy performance of morbidity-based forecasting for malaria commodities.

Commodity	MAE	Mean Error	Observations
ACT 6	3432	-1128	47
ACT 12	2824	1778	47

Continued

ACT 18	2431	776	47
ACT 24	11,883	9387	47
mRDT	64,170	64,170	47

Table 2 presents the forecast accuracy of the consumption-based forecasting approach for five malaria commodities over 47 monthly observations. The mean absolute error (MAE) ranged from 8711 packs for ACT 12 to 131,987 kits for malaria rapid diagnostic tests (mRDTs), indicating substantial forecasting errors across all commodities. Positive mean errors were observed for every product, demonstrating a consistent tendency toward overestimation. Compared with the morbidity-based approach, consumption-based forecasting produced markedly larger errors for all commodities, reflecting lower predictive accuracy. The largest errors were observed for mRDTs, where forecast quantities substantially exceeded actual consumption, likely due to distortions in historical logistics data caused by procurement practices, stockouts, and supply constraints.

Table 2. Forecast accuracy metrics for consumption-based quantification of malaria commodities in Zambia.

Commodity	MAE	Mean Error	Observations
ACT 6	11,750	9861	47
ACT 12	8711	8475	47
ACT 18	10,064	9361	47
ACT 24	18,551	14,657	47
mRDT	131,987	131,987	47

Figure 1 compares actual consumption of antimalarial commodities with forecasts generated using morbidity-based and consumption-based methods across the five commodities evaluated between 2022 and 2025. The figure demonstrates that morbidity-based forecasts closely follow observed consumption trends throughout the study period, indicating strong alignment between epidemiological demand and actual commodity utilization. In contrast, consumption-based forecasts increasingly diverge from observed consumption and consistently overestimate demand over time. This widening gap suggests that historical logistics data may embed distortions caused by stockouts, procurement inefficiencies, and other supply constraints, leading to progressively less accurate forecasts.

Figure 2 illustrates temporal trends in mean absolute error (MAE) for morbidity-based and consumption-based forecasting methods from 2022 to 2025. Morbidity-based forecasting maintained relatively stable and low MAE values throughout the 47-month study period, generally ranging from approximately 1100 to 2900 units, indicating consistent forecasting performance over time. In contrast, consumption-based forecasting exhibited progressively increasing errors, with MAE values rising from about 1200 - 4500 units in 2022-2023 to 9000 - 15,000 units in 2024 and 11,800 - 24,800 units in 2025.

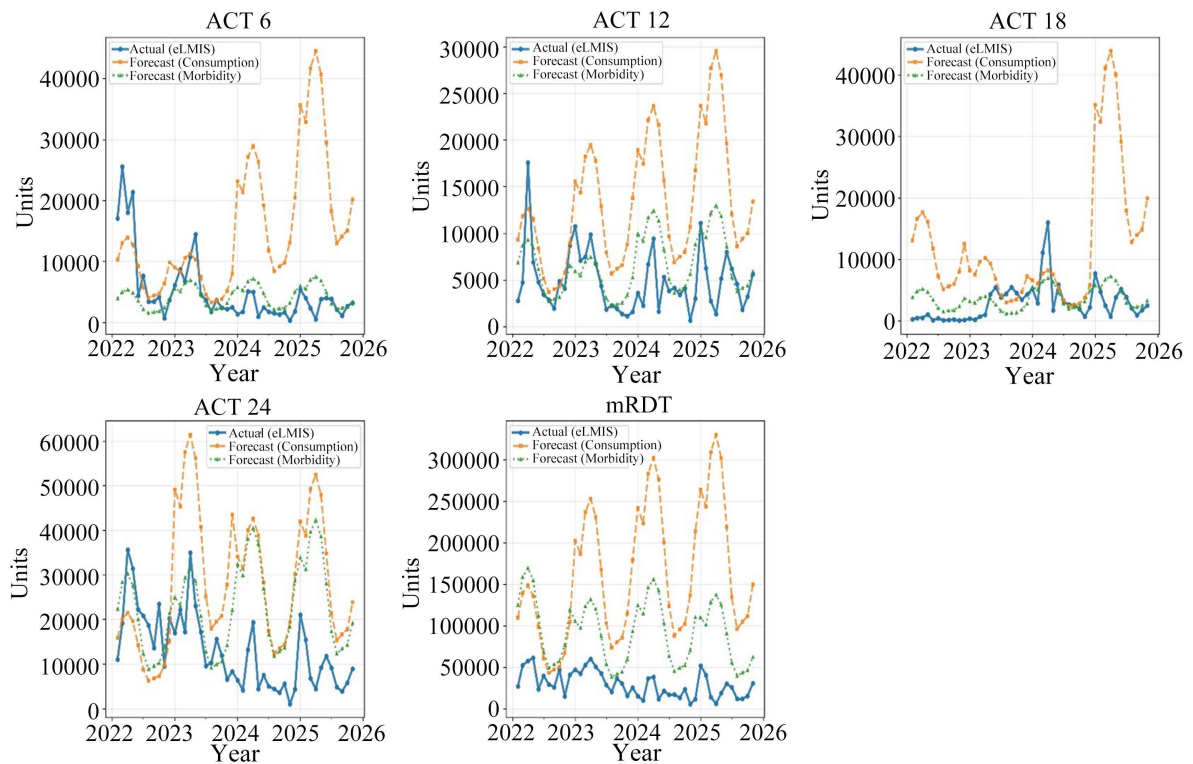


Figure 1. Actual consumption compared with morbidty-based and consumption-based forecasts for malaria commodities, 2022-2025.

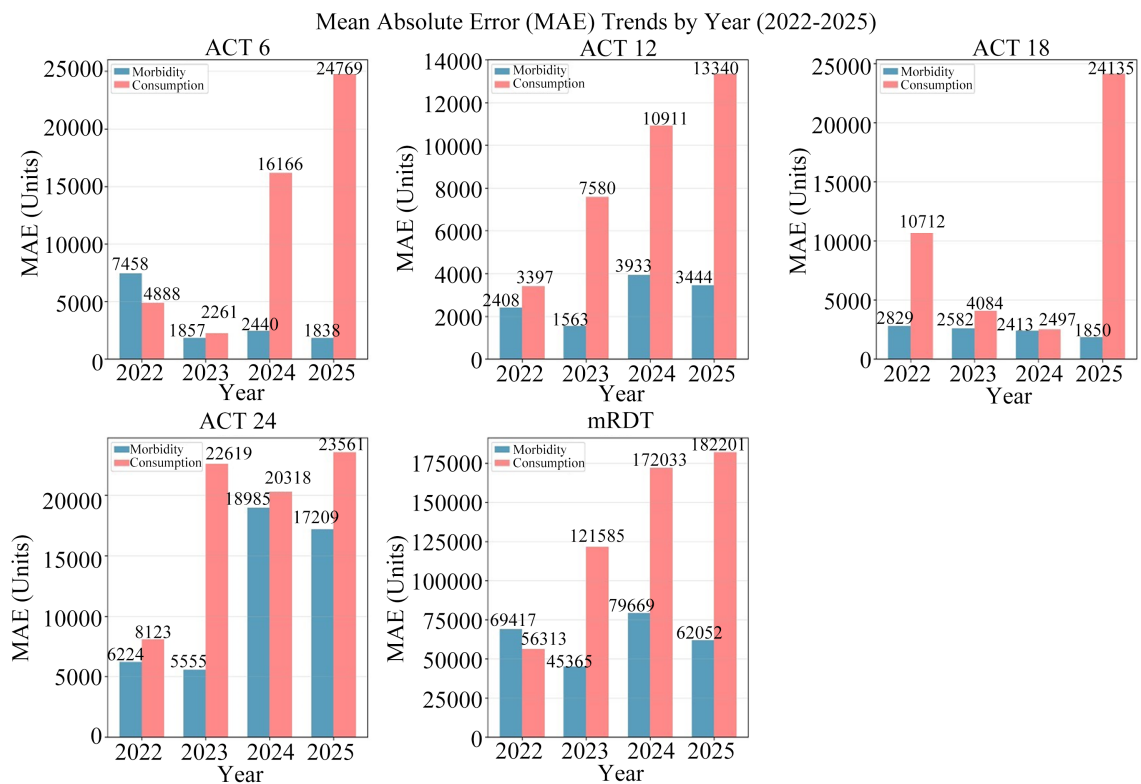


Figure 2. Trends in Mean Absolute Error (MAE) for morbidty-based and consumption-based forecasting methods, 2022-2025.

Figure 3 compares the distribution of forecast errors for morbidity-based and consumption-based forecasting methods across all malaria commodities. The figure shows that errors from the morbidity-based approach are more tightly clustered, with fewer and less extreme outliers, indicating greater precision and consistency. In contrast, consumption-based forecasting exhibits substantially larger errors, wider variability, and several extreme outliers, with error magnitudes generally three to four times higher than those observed with morbidity-based forecasting.

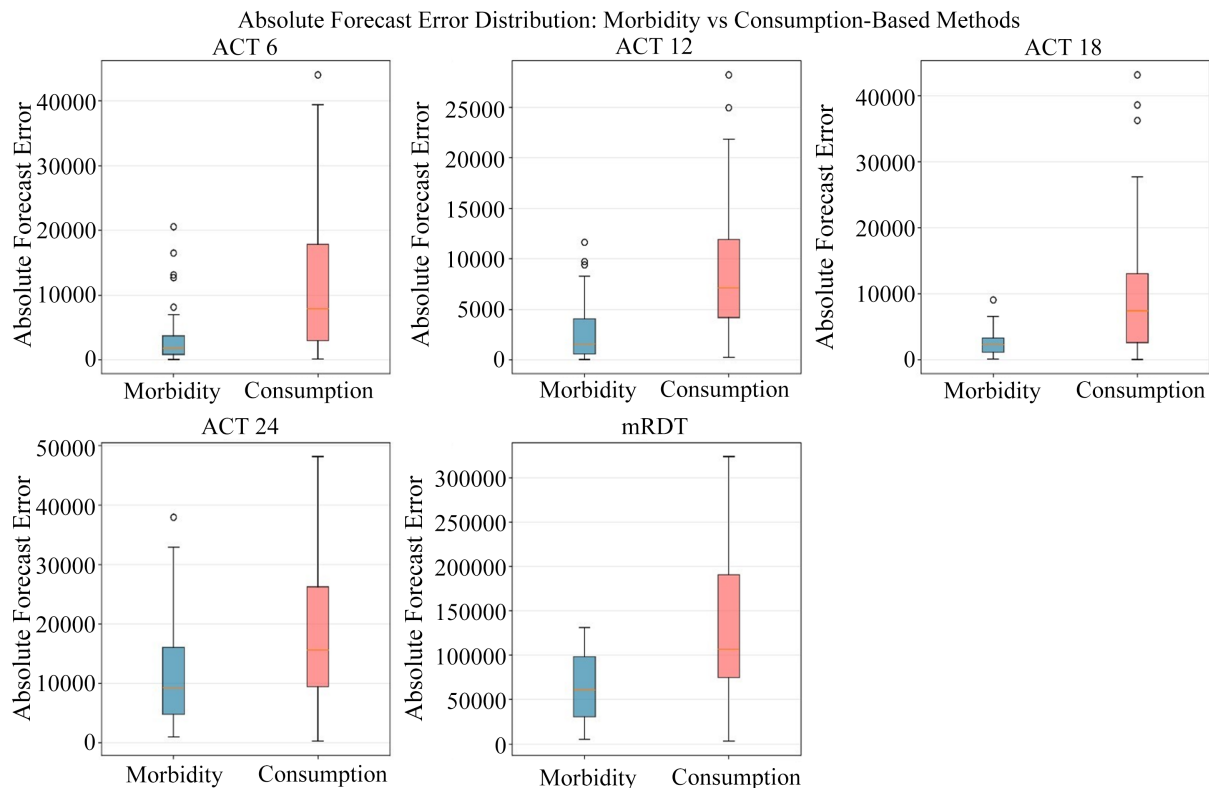


Figure 3. Distribution of forecast errors for morbidity-based and consumption-based forecasting methods.

Table 3 compares the forecasting performance of morbidity-based and consumption-based quantification methods for five malaria commodities between 2022 and 2025. Across all commodities, morbidity-based forecasting consistently produced lower mean absolute errors (MAEs) than consumption-based forecasting, demonstrating superior predictive accuracy. The absolute reduction in forecast error ranged from 5887 packs for ACT 12 to 67,817 kits for malaria rapid diagnostic tests (mRDTs). Percentage reductions in forecasting error ranged from 35.95% for ACT 24 to 75.85% for ACT 18, indicating substantial improvements in forecast precision. The ratio of consumption-based to morbidity-based errors (C/M) ranged from 1.56 to 4.14, showing that consumption-based forecasts generated between 1.6 and 4.1 times higher errors than morbidity-based forecasts. The greatest relative improvement was observed for ACT 18, while ACT 24 showed the smallest, though still meaningful, gain.

Table 3. Comparative forecast accuracy of morbidity-based and consumption-based quantification methods for malaria commodities in Zambia, 2022-2025.

Commodity	Morbidity MAE	Consumption MAE	Difference	Ratio (C/M)	Error Reduction %
ACT 6	3432	11,750	8318	3.42	70.79
ACT 12	2824	8711	5887	3.08	67.58
ACT 18	2431	10,064	7633	4.14	75.85
ACT 24	11,883	18,551	6669	1.56	35.95
mRDT	64,170	131,987	67,817	2.06	51.38

Figure 4 illustrates the extent to which morbidity-based forecasting improves forecasting accuracy compared with consumption-based forecasting for malaria commodities in Zambia. Forecast error reductions ranged from 35.95% for ACT 24 to 75.85% for ACT 18, with substantial improvements observed for other ACT formulations (67.58% - 70.79%) and mRDTs (51.38%). These findings demonstrate that morbidity-based forecasting consistently outperformed consumption-based methods across all commodities.

Error Reduction Percentage: Morbidity-Based vs Consumption-Based (2022-2025)

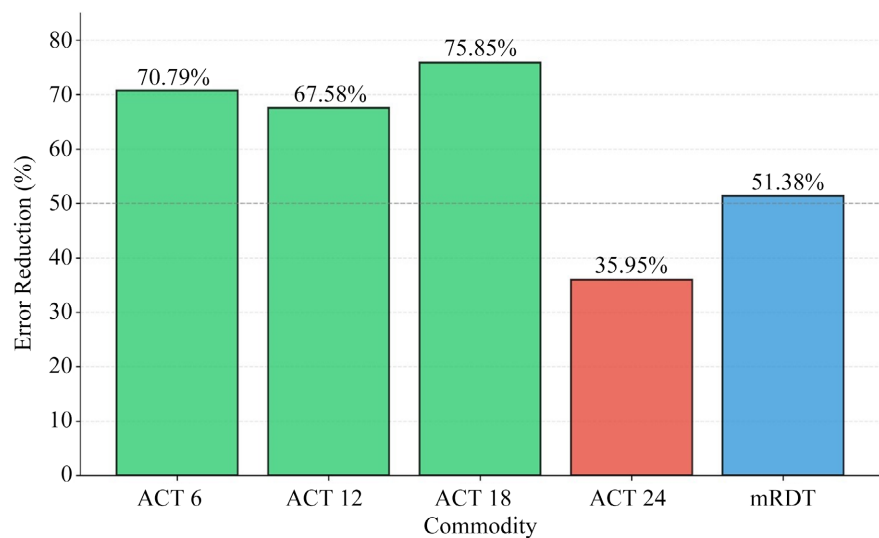
**Figure 4.** Percentage reduction in forecast error achieved by transitioning from consumption-based to morbidity-based forecasting for malaria commodities in Zambia.

Table 4 presents the results of the Wilcoxon signed-rank test comparing forecast errors between morbidity-based and consumption-based forecasting methods for five malaria commodities. Statistically significant differences were observed for all commodities, with W statistics ranging from 889 to 1010 and p -values $\leq 1.06 \times 10^{-6}$, providing strong evidence that morbidity-based forecasting

produced consistently lower errors than consumption-based forecasting. The effect sizes, measured using Cohen's *d*, ranged from 0.67 for ACT 24 to 1.22 for ACT 12, indicating moderate to very large practical significance. These findings demonstrate that the observed improvements are not only statistically significant but also operationally meaningful for pharmaceutical supply chain planning. In addition, the 95% confidence intervals for the mean differences did not cross zero for any commodity, confirming the robustness of the results. The lower standard deviations associated with morbidity-based forecasts across all commodities further indicate greater consistency and reduced variability compared with consumption-based forecasting.

Table 4. Wilcoxon signed-rank test comparing forecast errors between morbidity-based and consumption-based forecasting methods for malaria commodities in Zambia.

Wilcoxon signed-rank test Results								
Commodity	W_Statistic	Z_Score	p_Value	Cohens_d	CI_Lower_95	CI_Upper_95	Morb_SD	Cons_SD
ACT 12	1010	5.5591	0.000000000257	1.2152	4697.6	7368.96	2915.12	6387.38
ACT 18	909	4.4191	0.00000106	0.9979	4553.75	10537	1790.37	10541.91
ACT 24	971	5.1189	0.00000000448	0.6717	4625.92	9460.96	9438.04	11438.51
ACT 6	889	4.1933	0.00000427	1.0521	5561.45	12401.94	4157	11335.32
mRDT	980	5.2205	0.00000000163	1.1415	54334.64	88748.27	35393.51	81255.63

Table 5 presents the results of the Diebold-Mariano test, which formally compares the predictive accuracy of morbidity-based and consumption-based forecasting methods over the 47-month study period. Across all five malaria commodities, the median absolute errors were consistently lower for morbidity-based forecasts than for consumption-based forecasts, indicating superior predictive performance. The Diebold-Mariano statistics ranged from 3.31 for ACT 18 to 5.76 for malaria rapid diagnostic tests (mRDTs), with all corresponding *p*-values ≤ 0.001 . These highly significant results confirm that the improved accuracy of morbidity-based forecasting is statistically robust and unlikely to be due to random variation. The strongest evidence of superiority was observed for mRDTs, followed by ACT 24 and ACT 12, demonstrating that epidemiologically driven forecasting substantially outperformed consumption-based approaches across both pharmaceutical and diagnostic commodities.

Table 5. Diebold-Mariano test results comparing predictive accuracy of morbidity-based and consumption-based forecasting methods for malaria commodities in Zambia.

Diebold-Mariano Test Results					
Commodity	MAE_Med_Morb	MAE_Med_Cons	DM_Statistic	SE_DM	p_Value
ACT 12	1566	7287	4.786	21,300,000	0.000002
ACT 18	2227	6795	3.3127	60,700,000	0.000924

Continued

ACT 24	9214	16,200	4.9055	53,400,000	0.000001
ACT 6	1629	8131	3.6908	66,600,000	0.000224
mRDT	60,487	108,863	5.761	3,370,000,000	<0.000001

4. Discussion

This study compared the accuracy of morbidity-based and consumption-based forecasting approaches for malaria commodities in Zambia. The findings demonstrate that morbidity-based forecasting significantly outperforms consumption-based approaches, with mean absolute error (MAE) reductions ranging from 35.95% to 75.85%, consistent with foundational supply chain theory distinguishing between actual demand and observed consumption patterns. This aligns with established operations management concepts including demand signal distortion and information asymmetry in supply chains (Ionel & Miron, 2023).

A research study carried out in Kenya revealed a significant positive correlation between demand forecasting methods based on epidemiological trends and operational results, explaining about 70% of the differences in operational performance (Abuya & Okello, 2026). Error reductions of 35.95% - 75.85% align with Kenya comparative studies showing epidemiologically grounded forecasting captures 65% - 78% of demand variance (Abuya & Okello, 2026). While ACT tablets achieved low MAE values (2431 - 11,883 kits), high-volume commodities exhibited substantial residual errors. For mRDTs (MAE = 64,170 kits vs. actual mean consumption of 29,557), the large error reflects HMIS limitations in capturing test utilization beyond laboratory-confirmed diagnoses, as well as under-reporting of asymptomatic infections managed in community settings. The large error for ACT 24 (MAE = 11,883) may reflect differential prescription patterns across age groups and facility types not captured at national aggregation levels. These commodity-specific limitations require contextualized interpretation rather than claiming minimal bias overall (Abuya & Okello, 2026).

The findings of this study show that predictions based on consumption become less accurate over time, with errors increasing during the forecast period. This occurrence indicates a pronounced example of the bullwhip effect, which is well-documented in supply chain literature. It describes how small changes in consumer demand can lead to increasingly erratic procurement orders (Salwa & Zulfikri, 2024). Predictions based on morbidity data from malaria monitoring were reliably precise, with a mean absolute error ranging from 1100 to 2900 units over a span of 47 months. Nevertheless, consumption-based forecasts showed increasing volatility. MAE values rose from 1200 - 4500 units (2022-2023) to 9000 - 15,000 units (2024) and 11,800 - 24,800 units (2025), a 10-fold increase despite stable disease epidemiology.

This error amplification reflects bullwhip dynamics where minor morbidity fluctuations become distorted through procurement and inventory actions, with MAE values rising from 1200 - 4500 units (2022-2023) to 9000 - 15,000 units

(2024) and 11,800 - 24,800 units (2025) a 10-fold increase despite stable disease epidemiology. Facilities facing supply shortages chronically over-order to build safety stock buffers, embedding these procurement responses in historical consumption data that subsequently distort future forecasts. Morbidity-based approaches circumvent this problem entirely by anchoring demand estimates in epidemiological reality rather than procurement artifacts.

While this analysis focuses on malaria commodities in Zambia, the underlying principles generalize to other domains characterized by uncertain demand and constrained data environments. In retail distribution, demand-driven forecasting based on point-of-sale data consistently outperforms consumption-based methods distorted by promotional activities and inventory policies. In humanitarian logistics for refugee populations, epidemiological anchoring (population estimates) provides more stable demand signals than historical consumption records subject to funding volatility.

In public sector procurement for essential medicines, procurement records accumulate artifacts from supply constraints and rationing decisions identical to those observed in Zambian malaria supply chains. The framework presented here distinguishing actual demand from distorted consumption, applying population-based signals, and rigorously evaluating forecast accuracy offers a replicable approach for improving decision support systems across these contexts. Organizational barriers to implementation include staff capacity, model complexity, and data quality requirements implementation research is essential for translating these findings into practice (Bilal et al., 2024).

Morbidity-based forecasts showed error reductions of 35.95% to 75.85% over consumption-based methods with ACT formulations achieving substantially lower MAE values. However, residual errors for high-volume commodities, particularly mRDT (MAE = 64,170 kits vs. actual mean consumption of 29,557), indicate significant forecast bias. These larger errors likely reflect under-reported morbidity data for asymptomatic infections and malaria cases managed outside health facilities, limitations intrinsic to HMIS-derived morbidity signals. ACT commodities, by contrast, align more closely with clinical diagnoses, explaining their superior forecast accuracy.

Consumption-based forecasts become unreliable over time with MAE escalating to 9000 - 15,000 units in 2024 and 11,800 - 24,800 units by 2025 while morbidity-based approaches remained stable with MAE values of 1100 - 2900 units, proving superior reliability in dynamic supply chains. Wilcoxon signed-rank tests confirmed significant differences across all commodities (p -values ≤ 0.00000106) and effect sizes (Cohen's d 0.67 to 1.22). Innovations in healthcare supply chain management now integrate epidemiological data with procurement systems through demand-sensing approaches. Previous evidence has shown that triangulating supply and demand data improves the fulfilment of patient demands (Wang et al., 2022).

Furthermore, the integration of predictive analytics with procurement processes represents an emerging best practice with studies demonstrating that data-

driven forecasting approaches substantially enhance drug availability and reduce service disruptions. Thus, the evidence increasingly favors epidemiologically informed procurement strategies supported by robust evidence showing that consumption-based forecasts systematically overestimate demand while morbidity-based forecasts achieve lower error metrics of 35.95% to 75.85% with minimal bias, thereby offering meaningful improvements in supply chain decision-making and patient outcomes (Abuya & Okello, 2026).

The evidence unequivocally supports restructuring national procurement systems to base forecasts on epidemiological data rather than historical consumption patterns. Consequently, a 35.95% - 75.85% error reduction translates to operational benefits, including procurement reductions of 20% - 30%, while maintaining or improving service availability (Abuya & Okello, 2026). Moreover, this aligns with policy recommendations from supply chain research in African contexts emphasising data-driven decision-making and the integration of demand signals into procurement processes. Notably, implementation research identifies staff capacity, forecasting model complexity and data quality requirements as key determinants of successful adoption. Thus, organizational readiness is essential for translating these findings into practice (Bilal et al., 2024).

The present study therefore demonstrated that morbidity-based forecasting substantially outperforms consumption-based approaches for malaria commodities in Zambia aligns with established supply chain theory and therefore reflects emerging best practices in healthcare logistics. Therefore, this research provides actionable evidence for pharmaceutical supply chain transformation in African settings. The mechanisms underlying superior performance namely, a direct measurement of epidemiological demand signals, elimination of procurement-driven distortions and maintenance of temporal stability reflect fundamental supply chain principles with broad applicability beyond malaria commodities.

The marked reduction in forecasting errors suggests that adopting morbidity-based forecasting can substantially enhance procurement accuracy, reduce overstocking and stockouts, improve inventory turnover, minimize wastage and procurement costs, and strengthen overall commodity security for malaria control programs. The results of this study provide compelling statistical evidence that morbidity-based forecasting substantially outperforms consumption-based methods in predicting malaria commodity requirements in Zambia. Thus, this study provides a compelling foundation for policy reform and practice change across healthcare systems in resource-constrained settings.

4.1. Limitations and Strengths of the Study

This study has several limitations that should be considered. It relies on secondary routine data, which may be subject to reporting inaccuracies and inconsistencies in data quality across facilities. The relatively short study period may not adequately capture long-term epidemiological and demand trends. Additionally, the exclusion of environmental and seasonal predictors limits the ability to fully account for variations in malaria transmission dynamics. The analysis is also re-

stricted to selected malarial commodities which may affect the generalisability of the findings to other essential health products. Furthermore, the absence of hybrid forecasting models means that potentially more accurate combined approaches have not been explored.

Despite these limitations, this study has notable strengths. It utilises a nationally representative dataset covering all reporting health facilities thereby enhancing the generalisability and policy relevance of the findings. The direct comparison of forecasting approaches using identical datasets strengthens internal validity, whereas the application of multiple accuracy metrics and robust statistical tests ensures a comprehensive evaluation of model performance. In addition, the use of routine health system data enhances the programmatic relevance and real-world applicability of the results.

4.2. Policy, Practice, and Research Implications of Adopting Morbidity-Based Forecasting for Malaria Commodities in Zambia

The findings of this study have important implications for policy, practice, and future research (Table 6). Morbidity-based forecasting reduced forecast errors by 35.95% to 75.85% compared with consumption-based methods, providing strong evidence that epidemiologically driven forecasting offers a more accurate and reliable approach to malaria commodity quantification in Zambia. Institutionalizing this approach within national quantification guidelines could substantially improve procurement planning, inventory management, and commodity security by reducing stockouts, overstocking, expiries, and emergency procurement. Successful implementation will require strengthening routine health information systems, improving interoperability between the Health Management Information System (HMIS) and the electronic Logistics Management Information System (eLMIS), and investing in workforce capacity in forecasting, epidemiology, and supply chain analytics. The findings also highlight the potential for significant cost savings and more efficient use of limited health resources, while improving access to malaria diagnostics and treatment and ultimately contributing to reductions in malaria morbidity and mortality. Future efforts should focus on integrating climatic and environmental variables, developing hybrid and machine learning forecasting models, and evaluating the broader applicability of this approach to other essential medicines and disease programs across Zambia and sub-Saharan Africa.

Table 6. Policy, practice, and research implications of adopting morbidity-based forecasting for malaria commodities in Zambia.

Domain	Key Finding from This Study	Policy and Practice Implications	Recommendations
National forecasting policy	Morbidity-based forecasting reduced forecast errors by 35.95% - 75.85% compared with consumption-based methods.	National quantification guidelines should prioritize epidemiologically driven forecasting over approaches based solely on historical consumption data.	Revise National Malaria Elimination Programme (NMEP) quantification guidelines to institutionalize morbidity-based forecasting as the primary forecasting approach for malaria commodities.

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Pharmaceutical procurement	More accurate forecasts improve alignment between procurement quantities and actual disease burden.	Better procurement planning can reduce overstocking, understocking, expiries, and emergency procurement.	Integrate morbidity-based forecasts into annual procurement plans and tender specifications.
Supply chain management	Morbidity-based forecasting produced more stable and less variable forecast errors over time.	Improved demand estimation can enhance inventory positioning, warehouse efficiency, and distribution planning.	Use morbidity-based forecasts to guide buffer stock calculations, distribution schedules, and inventory replenishment.
Commodity security	Lower forecasting errors can reduce stockouts and improve continuous availability of antimalarial medicines and diagnostics.	Strengthened commodity security supports uninterrupted malaria diagnosis and treatment.	Adopt morbidity-based forecasting to ensure timely availability of artemether-lumefantrine formulations and mRDTs at all levels of care.
Health outcomes	Improved commodity availability is expected to enhance treatment coverage and reduce malaria morbidity and mortality.	Forecasting reforms can directly contribute to better patient outcomes and malaria control.	Link forecasting improvements to national malaria elimination strategies and universal health coverage goals.
Health information systems	Morbidity-based forecasting depends on accurate and timely HMIS case data.	Data quality becomes a critical determinant of forecasting performance.	Strengthen HMIS reporting, routine data quality audits, and interoperability with eLMIS and warehouse management systems.
Digital decision support	Forecasting effectiveness is enhanced by integrated analytics and automated quantification tools.	Decision-support systems can facilitate real-time forecasting and scenario modeling.	Develop dashboards and forecasting modules that combine HMIS, eLMIS, and climate data.
Workforce capacity	Successful implementation requires technical skills in quantification, epidemiology, and data analytics.	Human resource capacity is essential for sustaining forecasting improvements.	Provide training for pharmacists, supply chain specialists, and malaria programme staff in morbidity-based forecasting and statistical analysis.
Financial efficiency	Reduced forecasting errors can lower wastage, storage costs, and emergency procurement expenditures.	More efficient resource use improves value for money in donor and government investments.	Conduct cost-effectiveness analyses and reinvest savings into strengthening malaria control programs.
Seasonal preparedness	Morbidity-based forecasting is better aligned with seasonal malaria transmission patterns.	Forecasts can be adjusted proactively before high-transmission periods.	Incorporate rainfall, temperature, and epidemiological trend data into routine forecasting.
One Health and climate resilience	Malaria transmission is influenced by environmental and climatic factors.	Forecasting systems should account for ecological drivers of disease burden.	Develop hybrid models integrating morbidity, climate, and environmental indicators.
Governance and accountability	More transparent forecasting enhances evidence-based decision-making.	Strong governance improves procurement accountability and stakeholder confidence.	Establish routine forecasting performance reviews using MAE, Wilcoxon, and Diebold-Mariano metrics.
Research and innovation	Residual errors, particularly for mRDTs, indicate opportunities for further methodological refinement.	Continued innovation is needed to optimize forecasting accuracy.	Support multicentre studies evaluating hybrid and machine learning forecasting models.

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Regional applicability	The forecasting framework is applicable to other disease programmes and African health systems.	Lessons from Zambia can inform broader pharmaceutical supply chain reforms.	Adapt and scale the model to other essential medicines and diagnostics in sub-Saharan Africa.
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5. Conclusion

Morbidity-based forecasting provides a more accurate and epidemiologically grounded approach to malaria commodity quantification than traditional consumption-based methods in Zambia. By aligning supply planning with disease burden rather than historical utilisation, this approach addresses key limitations associated with stock-dependent consumption data and improves the reliability of demand estimates. The adoption of morbidity-driven forecasting within national supply chain systems has the potential to reduce stockouts, optimise resource allocation, and strengthen malaria control efforts. Future research should focus on integrating climatic and seasonal variables and developing hybrid forecasting models to further enhance predictive performance in dynamic transmission settings.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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