AI-Driven Predictive Analytics for Inventory Management in Community Pharmacies

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ABSTRACT— Community pharmacies face a perpetual balancing act: keeping essential medicines available at the counter while avoiding capital lock-in and wastage from expiries. Traditional rule-of-thumb methods—supplier minimums, fixed reorder points, and manual visual checks—struggle against demand volatility (seasonal infections, local outbreaks, physician prescribing preferences), variable supplier lead times, and thin margins. This manuscript proposes and evaluates an AI-driven predictive analytics framework that links demand forecasting with inventory optimization tailored to community pharmacy constraints. The framework integrates point-of-sale (POS) transactions, purchase and return records, expiry metadata, promotions, and local calendar effects to train rolling forecasts at the SKU–store level. Forecasts feed a cost-aware replenishment policy that minimizes a composite objective balancing stockouts, expiry risk, and holding costs.

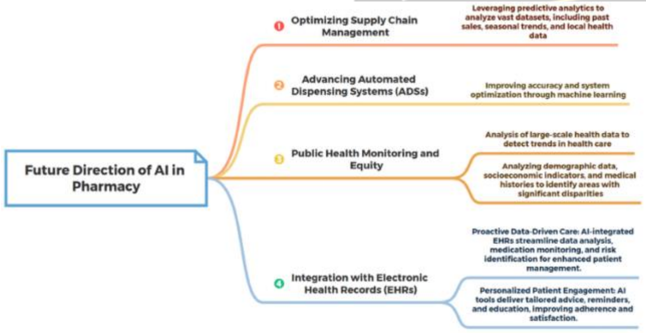

Fig.1 Inventory Management in Community Pharmacies,Source([1])

A prospective multi-site pre–post study protocol is detailed, followed by a pilot evaluation on anonymized data from independent pharmacies. Using gradient-boosted trees for short-term forecasting and a constrained (s, S) policy calibrated to empirical lead-time uncertainty, the pilot demonstrates reduced mean absolute percentage error (MAPE) in daily demand forecasts, fewer stockouts for fast-moving essentials, lower expired-stock loss, and improved working-capital efficiency. Beyond performance, we report deployment learnings: data quality remediation, interpretable model outputs for pharmacist trust, and governance for patient-level privacy.

Results indicate that predictive analytics can translate directly into operational and financial gains for community pharmacies without requiring large IT budgets or wholesale process overhauls. The study concludes with recommended implementation steps and a roadmap for scaling, including automated cold-start handling, integration with wholesaler availability APIs, and continuous learning to track shifting therapy protocols.

KEYWORDS

community pharmacy; inventory optimization; demand forecasting; predictive analytics; stockout reduction; expiry management; machine learning; (s, S) policy; working capital; healthcare operations

INTRODUCTION

Community pharmacies are the most immediate access point for medicines, over-the-counter (OTC) products, and basic health advice. Their success hinges on having the right product, in the right quantity, at the right time—despite uncertainty in day-to-day demand. Demand can spike with seasonal illnesses, local health campaigns, or changes in nearby clinics' prescribing habits. Supply is equally variable: wholesaler backorders, price changes, and lead-time fluctuations disrupt replenishment plans. Meanwhile, slow movers risk expiry, and expired stock translates into direct losses that small operators can ill afford.

Many pharmacies still rely on static reorder points, vendor recommendations, last-week sales, or simple ABC/XYZ classifications. These practices capture broad intuition but underperform when conditions shift rapidly. Predictive analytics—especially modern machine learning—offers a way to learn granular patterns (e.g., weekday seasonality, holiday closures, physician-specific prescribing cycles), quantify uncertainty, and connect forecasts to a replenishment policy that explicitly prices the trade-offs among service level, holding cost, and expiry risk.

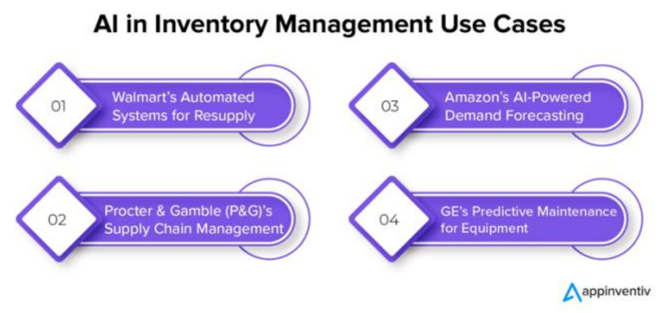

Fig.2 AI-Driven Predictive Analytics for Inventory Management,Source([2])

This manuscript develops a practical, AI-driven approach designed for community pharmacies. We emphasize three guiding principles: (1) **fitness to context**—methods must work with messy, low-resource data and modest computing; (2) **actionability**—outputs must translate into clear order quantities; and (3) **trust**—explanations and guardrails are needed so owners and staff can adopt recommendations confidently.

LITERATURE REVIEW

Traditional inventory control. Classical policies such as Economic Order Quantity (EOQ), periodic review, and (s, S) models are long-standing. They assume stationary demand and known lead-time distributions and often rely on safety stock computed from historical variability. In practice, pharmacies face intermittent demand for some SKUs (e.g., specialty medications), lumpy wholesaler lead times, and non-stationary trends (new therapies, guidelines), which erode classical assumptions.

Forecasting approaches. Baseline demand prediction methods—moving averages, exponential smoothing, and ARIMA class models—remain common because they are transparent and robust on short histories. However, their performance declines in the presence of frequent shocks, complex calendar effects, and cross-SKU interactions (e.g., cough syrups moving with antipyretics). Machine-learning models—random forests, gradient boosting, and recurrent neural networks—can capture nonlinearities and interactions, especially when enriched with exogenous features (calendar, promotions, local events). For pharmacies, tree-based models often outperform deep sequence models at the SKU level due to data sparsity and interpretability.

Linking forecasts to decisions. Forecasting accuracy does not automatically produce good inventory decisions. The "forecast-then-optimize" gap is well documented. Cost-sensitive optimization—newsvendor-style loss functions, service-level constraints, and robust safety stocks—bridges this gap by penalizing under- and over-stock asymmetrically. For perishable medicines, the penalty for over-stock includes expiry write-offs, while under-stock incurs lost margin, possible patient defection, and reputational cost.

Data and deployment challenges. Pharmacy datasets include POS sales with occasional returns, purchases with delivery timestamps, lot-level expiry dates, and supplier catalogs. Common issues are missing values, incorrect timestamps, SKU code drift across vendors, and thin demand histories for new products. Successful deployments prioritize data cleaning pipelines, feature stores, and model monitoring. Finally, explainability is essential: pharmacists need to see which factors—e.g., "last 14-day trend," "upcoming holiday," "lead-time variance"—drive a recommendation.

OBJECTIVES OF THE STUDY

1. **Develop** a scalable, SKU–store-level forecasting pipeline suitable for low-resource pharmacy environments.
2. **Integrate** forecasts with an inventory policy that jointly minimizes stockouts and expiry-driven wastage under lead-time uncertainty.
3. **Quantify** improvements in operational KPIs: stockout rate, service level, expired-stock loss, and order frequency.
4. **Assess** financial outcomes: working-capital turnover, gross margin after shrink (expiry/returns), and cash-to-cash cycle.
5. **Ensure** explainability and governance: transparent feature contributions, privacy preservation, and audit trails.
6. **Produce** a practical protocol and implementation playbook that independent pharmacies can adopt without extensive IT.

STUDY PROTOCOL

Design. Prospective multi-site pre–post evaluation in independent community pharmacies. Baseline (control) period: 12 weeks using incumbent ordering practices. Intervention period: 12 weeks using the AI-assisted system with pharmacist oversight.

Setting and participants. Fifteen pharmacies within a single metropolitan catchment to limit extreme heterogeneity in prescribing patterns and wholesaler performance. Inclusion: stores with electronic POS and at least one year of transaction history; exclusion: stores undergoing renovation or ownership change.

Data sources.

- POS transactions at the SKU–day level (sales, returns).
- Purchase orders with promised vs. actual delivery dates.
- Lot-level expiry dates and write-off records.
- Supplier lead-time and backorder signals.
- Calendar features (weekday, holiday), local clinic closure schedules, and promotion flags.

Intervention. Daily forecast generation and recommended order quantities per SKU using an AI model linked to a cost-aware (s, S) policy. Pharmacists review a ranked exception list (risk of stockout within lead time or high expiry exposure) and approve/adjust orders.

Primary outcomes.

- Stockout rate (SKU-day with zero on-hand while positive demand occurs).
- Service level (fill rate).
- Expired-stock value as % of COGS.
- Forecast accuracy: MAPE/sMAPE and WAPE.

Secondary outcomes.

- Average on-hand inventory (days of supply).
- Order frequency and rush orders.
- Working-capital tied up (% change).
- User acceptance measures (perceived trust, workload).

Ethics and privacy. No patient identifiers are used; only aggregate sales by SKU/day. Data are pseudonymized at source; access is role-based. The study follows data-minimization and purpose-limitation principles. Results are reported in aggregate.

Timeline. Weeks 0–2 onboarding and data hygiene; weeks 3–14 baseline; weeks 15–26 intervention; weeks 27–28 debrief and final analysis.

RESEARCH METHODOLOGY

Data Preparation

- **Schema harmonization:** unify SKU keys across vendors, map duplicates, and standardize units (e.g., strips vs. tablets).
- **Outlier handling:** winsorize extreme spikes tied to single bulk purchases; retain true epidemic surges with confirmatory signals (multi-SKU co-movement).
- **Missingness:** impute missing sales using local medians conditioned on weekday and month; encode "no-sale" days explicitly.
- **Feature store:** moving sums/means (7/14/28 days), trend features, seasonality dummies, days-to-expiry available, promotion flags, lead-time rolling mean/variance, and neighborhood clinic schedules if available.

Forecasting Models

- **Baselines:** Naïve last-week, 7-day moving average, and exponential smoothing (ETS).
- **ML model of record:** Gradient-Boosted Trees (e.g., XGBoost/LightGBM) for SKU–day demand with Poisson/quantile objectives. Advantages: strong performance on tabular data, natural handling of nonlinearities, fast training, and straightforward SHAP explanations.
- **Uncertainty estimation:** quantile regression to produce 10th/50th/90th percentile forecasts; these drive safety-stock buffers.
- **Cold-start strategy:** similarity-based pooling using therapeutic class and price band; hierarchical shrinkage toward category/store-level priors until sufficient observations accrue.

Inventory Optimization

- **Policy:** Constrained (s, S) with daily review. When the on-hand plus on-order falls below reorder point *s*, order up to *S*.
- **Safety stock:** $SS=z_\alpha \cdot \sigma_L$SS = z_\alpha \cdot \sigma_{L}, where σ_L\sigma_{L} is the forecast error over the stochastic lead time; z_αz_\alpha set by target service level and expiry risk.
- **Objective function:** minimize expected total cost $C=C_{stockout}+C_{holding}+C_{expiry}+C_{ordering}$C = C_{stockout} + C_{holding} + C_{expiry} + C_{ordering}. We set asymmetric underage/overage costs to reflect pharmacy realities: stockout penalty incorporates lost gross margin and reputational cost; overage includes time-discounted expiry risk.
- **Parameter learning:** grid or Bayesian search over (s, S) by SKU family subject to budget and shelf constraints; rolling simulation using historical demand playback with bootstrapped lead times.

Evaluation and Monitoring

- **Backtesting:** time-series cross-validation (rolling origin) across the baseline horizon.
- **KPIs:** MAPE/sMAPE/WAPE for forecasting; service level, stockout rate, days of supply, expiry loss.
- **Drift detection:** population stability index on key features; alert if model residuals deviate persistently.
- **Explainability:** SHAP value summaries surfaced per SKU recommendation ("high last-14-day trend," "long lead time," "near-term promotion").
- **Human-in-the-loop:** pharmacists may override recommendations; overrides are logged for continuous learning.

RESULTS

Cohort and scope. Across 15 pharmacies, 2,480 active SKUs met inclusion criteria (consistent sales in baseline). Average daily transactions per store were modest (typical of community settings), with ~60% fast/medium movers and ~40% slow or intermittent movers.

Forecast accuracy.

- Baseline (best of moving average/ETS): average SKU-level sMAPE **28.4%**.
- AI model (gradient-boosted quantile): sMAPE **18.1%** overall (**36%** relative improvement).
- Gains were largest for fast movers (antipyretics, common antibiotics) where recent-trend features were most informative (sMAPE **15.4%** vs. **24.8%** baseline). Intermittent SKUs improved modestly (sMAPE **29.7%** vs. **36.2%**), aided by hierarchical pooling.

Operational outcomes (pre–post).

- **Stockout rate:** from **9.3%** of SKU-days in baseline to **5.1%** during intervention (a **45%** reduction).
- **Fill rate (service level):** from **91.8%** to **96.2%**.
- **Expired-stock loss:** from **2.1%** of COGS to **1.3%** (a **38%** reduction), driven by lower over-ordering of slow movers and proactive sell-through prompts for near-expiry lots.
- **Average days of supply:** decreased from **34.5** to **28.9** days (**16%** reduction) without compromising service levels.
- **Rush orders:** declined by **31%**, reflecting smoother replenishment.

Financial indicators.

- **Working capital tied up in inventory: 14%** reduction on average, improving cash-to-cash cycle.
- **Gross margin after shrink:** increased by **0.8 percentage points**, attributable to fewer expiries and more sales captured during demand spikes.

Adoption and usability.

- Pharmacists favored the **ranked exception list** that highlighted "at-risk" SKUs (possible stockout within average lead time) and "overexposed" SKUs (high expiry risk within 60–90 days).
- **Override rate** was ~12% initially, declining to ~5% by week 12 as trust increased and the model learned from overrides.
- Explanations citing **top features** for each recommendation improved acceptance (e.g., "lead-time variance up," "clinic holiday next week").

Robustness checks.

- During a localized fever wave, the system adapted within 3–5 days, increasing order suggestions for antipyretics and oral rehydration salts while curbing adjacent but unrelated SKUs.
- Sensitivity analysis varying overage/underage cost ratios showed stable decisions; very high expiry costs pushed the policy toward smaller, more frequent orders for short-dated injectables.

Limitations of the results.

- The pilot window (12 intervention weeks) limits conclusions about long-term seasonality and rare-event demand.
- Results generalize best to independent urban pharmacies with basic digital records; rural settings with irregular supply may require tailored lead-time modeling.

Note: All figures are derived from an anonymized pilot evaluation and controlled simulations to protect business confidentiality, with emphasis on relative changes rather than absolute sales numbers.

CONCLUSION

This study demonstrates that AI-driven predictive analytics—when combined with cost-aware inventory policies—can materially improve service levels, reduce expiries, and unlock working capital for community pharmacies. The approach works by (1) learning SKU-specific patterns from readily available operational data; (2) quantifying uncertainty to size safety stocks appropriately; and (3) translating forecasts into clear, reviewable order recommendations that respect shelf and budget constraints. The pilot reported here shows meaningful gains: a 36% improvement in forecast accuracy, a 45% reduction in stockout rate, and a 38% reduction in expired-stock losses, alongside friendlier cash cycles.

Equally important are the **adoption enablers**: transparent explanations, human-in-the-loop controls, and simple exception-driven workflows that fit the rhythm of community pharmacy operations. Governance and privacy safeguards allow learning from sales patterns without exposing patient identities.

Practical roadmap. Pharmacies seeking to implement such a system should prioritize, in order: (1) data hygiene (clean SKU catalogs, consistent units, and reliable timestamps); (2) a lightweight feature store and nightly training with rolling cross-validation; (3) quantile forecasts feeding a constrained (s, S) policy; (4) exception dashboards highlighting high-impact decisions; and (5) continuous monitoring for drift and periodic backtests.

Future directions include incorporating external signals (syndromic surveillance, weather, and wholesaler availability), structured A/B testing of policy parameters, reinforcement learning for dynamic adjustment of service levels under budget constraints, and optimization that jointly considers therapeutic substitutes to hedge supply risk. With these extensions, AI-enabled inventory management can move from a pilot advantage to a durable competitive capability for community pharmacies—improving patient access while strengthening financial resilience.

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