SUPPLY CHAIN MANAGEMENT

Intelligent Food Manufacturing Supply Networks in Saudi Arabia: Integrating AI-Based Production Forecasting, Digital Distributor Coordination and Sustainable Market Expansion under Vision 2030

Mohammad Al Junaidi

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Abstract

Saudi food manufacturers face a coupled planning problem: volatile regional demand must be translated into perishable production, distributor replenishment and electricity-intensive cold-chain decisions without sacrificing food safety or affordability. This critical integrative review examines thirty peer-reviewed contributions published between 2020 and 2025 and develops an implementable network architecture connecting probabilistic forecasting, constrained production optimisation, shared distributor signals and energy-aware operational control. Rather than equating prediction accuracy with commercial success, the analysis distinguishes forecast calibration, decision quality, network resilience and realised environmental outcomes. It identifies four mechanisms through which digital coordination can improve performance: faster detection of demand shifts, explicit shelf-life allocation, coordinated regional replenishment and alignment of processing and refrigeration with power-system constraints. Countervailing risks include biased distributor data, inconsistent product identifiers, capacity bottlenecks, cyber exposure and the potential for waste to migrate between network partners. A staged governance framework is proposed for Saudi manufacturers, industrial zones and distribution partners, supported by outcome measures that jointly assess service, expiry losses, electrical reliability, working capital and energy intensity. The review finds persuasive conceptual and transferable empirical support for integrated decision systems, but insufficient Saudi plant-level causal evidence to assume that sophisticated artificial intelligence will outperform well-governed statistical baselines. Future research should therefore prioritise prospective multi-site pilots, distributional fairness, counterfactual environmental accounting and electricity-disruption stress testing. The resulting agenda advances Vision 2030 objectives for industrial capability, food security and competitive domestic and export markets while preserving explicit human accountability.

Keywords: artificial intelligence; food manufacturing; demand forecasting; digital distributors; production scheduling; electrical infrastructure; Saudi Vision 2030; sustainability

1 Introduction

Saudi Arabia's food manufacturing sector sits at the intersection of industrial diversification, food security, population-driven consumption and the geography of a hot, arid trading economy. Manufacturers must transform imported and domestic inputs into safe, saleable products while managing changing retail promotions, institutional demand, regional travel patterns and distributor inventories. Conventional monthly plans can conceal simultaneous overproduction in one city and shortages in another. Refrigeration, freezing, packaging and hygienic processing also place demands on electrical infrastructure. A national digital ambition does not eliminate these physical limits; it makes their coordination more consequential.

The supplied Saudi manufacturing review establishes an starting point: digital visibility may support both supply-chain resilience and sustainability, but implementation conditions, regulation and network dynamism alter the result [1]. Research on food-sector digital supply chains similarly connects information integration with operational performance [2]. Nevertheless, neither technological adoption nor a lower forecast error is sufficient proof of reduced food loss. Forecasts become valuable only when planners can convert them into feasible batch sizes, distributor allocations and transport schedules before ingredients deteriorate or delivery windows close. Evidence from pandemic-era food planning illustrates the benefit of coordinating forecasting and rolling-horizon operational decisions under disruption [3].

Three disconnects motivate this paper. First, literature frequently evaluates prediction models independently of shelf-life, changeover time, energy constraints and cost-to-serve. Second, manufacturers and distributors often optimise different objectives: the factory favours stable utilisation while distributors demand frequent replenishment and flexible promotional response. Third, market expansion can increase utilisation and export reach while simultaneously raising kilometres travelled, packaging needs and cooling emissions. These conflicts require a network-level perspective rather than a list of promising digital tools. The present review consequently treats artificial intelligence as one component of an accountable socio-technical decision system, not an autonomous substitute for production judgement.

2 Aim, objectives and analytical questions

The aim is to develop and critically assess an integrated planning framework for intelligent Saudi food manufacturing supply networks that connects demand signals, factory operations, distributor decisions and sustainable market expansion. Four objectives structure the analysis: evaluate the evidence for multi-horizon demand forecasting; translate predictions into shelf-life-aware and electricity-aware production choices; specify interoperable coordination mechanisms between manufacturers and distributors; and define a balanced evaluation of service, economic viability, resilience and environmental performance.

The guiding questions ask when artificial intelligence adds value beyond simpler forecasting methods; which shared data and decision rights make distributor coordination trustworthy; how industrial electrical limits change the optimal production plan; and which evidence would establish that a digitally enabled regional expansion is genuinely sustainable. The contribution is conceptual and design-oriented. It does not report a newly collected Saudi factory dataset, a validated causal intervention or measured national savings.

3 Review methodology and evidence appraisal

This paper uses a transparent critical integrative review rather than claiming an exhaustive database screening exercise. The uploaded 2025 Saudi manufacturing review supplied the structural model of an introduction, explicit objectives, review method, technology analysis, resilience discussion and integrated implications [1]. The reference list was not inherited uncritically: publication metadata and DOI information were checked against discoverable journal, university or bibliographic records before inclusion.

The analytic corpus comprises thirty DOI-bearing works dated 2020–2025. Relevance was judged against five linked themes: forecasting and inventory decisions; perishable food operations and

wastage; interorganisational digital integration; resilience and human-centred governance; and energy or environmental accountability. Food-specific operational studies were prioritised for direct claims, while broader manufacturing papers were used only to explain transferable mechanisms or implementation constraints. Thematic synthesis compared the decision variable studied, evidence type, geographical transferability, reported outcomes and unresolved assumptions. Conceptual contributions were distinguished from field evaluations, simulated disruption studies and life-cycle assessments. No count of records retrieved or excluded is asserted because a reproducible systematic search and duplicate-screening protocol were not performed.

Critical assessment adopted four tests. Construct validity asked whether an article measured demand, sales, shipments, food loss or another outcome; these quantities must not be conflated. Operational validity asked whether the suggested forecast could actually inform manufacturing lead times, minimum batches, cleaning cycles or transport capacities. External validity assessed climatic exposure, distributor fragmentation and electricity dependence when transferring evidence to Saudi Arabia. Finally, sustainability validity required attention to the full change in waste, energy, logistics and computational burdens rather than selected efficiency indicators. The review includes methodological studies such as forecasting competitions [4], interpretability models [5], digital integration analyses [6], [7], resilience research [8]–[10] and environmental assessment [11]–[14]. Their heterogeneous methods preclude a pooled effect size. Conclusions are therefore conditional propositions and testable recommendations rather than a meta-analytic average.

Limitations remain. Bibliographic discoverability is not an independent full-text critical appraisal of every source; studies may have unreported selection biases or context-specific datasets. Research conducted outside Saudi Arabia cannot establish Saudi effect sizes. Moreover, review evidence published through 2025 does not resolve fast-changing model architectures, utility tariffs or data-governance arrangements in 2026. These boundaries are explicitly carried into the proposed evaluation design.

4 Saudi manufacturing context and electrical interdependence

Saudi demand is neither geographically uniform nor fully observable from orders. Large metropolitan markets, secondary cities, hospitality districts and industrial catering channels exhibit different product mixes and purchasing calendars. Manufacturers supply both shelf-stable foods and highly perishable dairy, bakery, chilled and frozen products. Distributor warehouses may hold partially visible inventories, so a factory shipment can appear as demand even where final consumption is weak. The national industrial and logistics agenda creates a policy rationale for better localisation and export readiness, but commercial feasibility must be demonstrated at product-region level.

Electrical infrastructure introduces a second system of constraints. Cold rooms and refrigerated vehicles require uninterrupted thermal control; production lines depend on motor drives, compressors, conveyors, pasteurisation, filling and packaging. Grid reliability, transformer headroom, voltage disturbances, generator readiness and the scheduling of maintenance can each cap safe throughput. Some equipment is flexible across hours, whereas continuous cold storage is not. A planner optimising nominal factory efficiency may inadvertently create a peak-demand excursion or an unsafe cooling bottleneck. Thus electricity should enter decision models through metered equipment demand, available feeder capacity, critical-load classification and outage-recovery procedures, not merely an assumed unit cost.

Digital twins and connected equipment can link factory operating conditions to replenishment decisions [15]. However, a simulated representation is useful only when physical states are current, sensor calibration is controlled and operators can override recommendations. Saudi applications should model high ambient temperatures and extreme summer cooling loads, considering product thermal stability before energy arbitrage. Substituting delayed refrigeration for a cheaper electricity period is unacceptable if food-safety boundaries would be crossed. A responsible optimisation model protects non-negotiable quality and safety requirements before seeking commercial savings.

5 AI-based demand forecasting: Methods, validity and limitations

A factory-level forecast should represent demand by stock-keeping unit, destination, channel and planning horizon. Historical invoices alone are inadequate: orders may reflect distributor forward buying, minimum order quantities, promotions, stockouts or transport disruptions rather than consumer consumption. Training data should distinguish sell-through from sell-in, record returns and expiry, and reconcile product identifiers across retailer, distributor and enterprise systems. Using retrospectively observed promotions or stock corrections creates leakage and deceptively high retrospective accuracy.

A defensible model hierarchy begins with seasonal naïve forecasts, exponential smoothing and intermittent-demand methods before testing gradient boosting, recurrent networks or attention-based architectures. The M5 retail competition demonstrates why broad benchmarking across disaggregated series matters [4]. Temporal Fusion Transformers offer multi-horizon predictions and explanatory indicators, although attention summaries do not prove causal influence [5]. Surveys of deep learning distinguish useful representation learning from challenges involving data hunger, interpretability and distribution shifts [16]. Model choice should therefore follow decision value and forecast calibration, not novelty. Sparse Saudi regional products may benefit more from pooled hierarchical models or carefully calibrated statistical shrinkage than from an individual deep network.

Forecast evaluation must reproduce the decision environment. Rolling-origin tests should preserve seasonal transitions, planned promotion lead times, missing distributor periods and new-product launches. Weighted absolute error alone can favour large-volume items while obscuring the financial impact of short-shelf-life stockouts. Pinball loss at actionable quantiles, bias by city, spoilage-weighted error and prospective service performance should complement aggregated accuracy. Quantile predictions allow planners to examine upper-tail demand without assuming symmetric uncertainty. Where product shelf-life is shorter than the forecast horizon, uncertainty in production yield and distributor stock is as important as future demand variation.

A bakery life-cycle case links machine-learning-based ordering to lower returns, but its measured environmental benefits depend on the particular products, baseline and allocation assumptions [11]. Studies of digital canteen management likewise connect predictive tools with food-loss decisions without establishing universal gains in manufacturing [17]. These findings support operational trials, not a general promise of fixed percentage savings. A model with lower error can increase waste if sales teams respond by expanding assortment or raising minimum stock levels. Conversely, a slightly less accurate but well-calibrated model may improve profitability through safer inventory quantiles. The appropriate selection criterion is the realised cost of the decisions driven by its predictions.

Concept drift warrants formal monitoring. Promotional intensity, tourism flows, retail concentration and import constraints may change demand-generating processes abruptly. Alert thresholds should

track directional bias, prediction-interval coverage, unseen product combinations and the proportion of decisions overturned by planners. Retraining should be triggered by documented degradation rather than an arbitrary calendar. Human overrides need reasons and later review, because they can reveal missing commercial information or introduce systematic optimism. The desired operating model combines learning with disciplined forecast governance.

Table 1. Analytical comparison of forecasting approaches for Saudi food manufacturing.

Approach	Core advantage	Primary limitation	Suitable decision and validation
Seasonal statistical baseline	Transparent and inexpensive	Weak on abrupt promotions	Short-horizon stable SKU; rolling-origin bias
Hierarchical pooled model	Shares signal across regions	Can conceal local shifts	Sparse city/SKU demand; coherent aggregates
Gradient boosting	Handles calendar and sales covariates	Leakage and drift sensitivity	Weekly distributor replenishment; quantile loss
Deep multi-horizon model	Learns nonlinear temporal interactions	High data and monitoring burden	Rich histories; calibration and ablation checks
Probabilistic ensemble	Expresses risk and tail demand	Can be poorly calibrated	Safety stocks; interval coverage and cost
Planner-adjusted forecast	Captures exceptional local knowledge	Overconfidence and incentive bias	New promotions; documented override audit

6 Intelligent production planning and energy-aware optimisation

Forecasts must be converted into a feasible plan spanning procurement, ingredients, batch sequencing, sanitation, packaging, storage and distribution. Mixed-integer programming can represent minimum production batches, recipe bills of material, allergen cleaning, line eligibility, labour shifts and shelf-life deadlines. A rolling horizon revises near-term quantities as sell-through becomes available while stabilising frozen production windows to protect operators and suppliers. Food-specific planning evidence supports coupling accurate demand information with recourse decisions during turbulent periods [3], [18].

Let production quantity for product i and period t be x(i,t), regional allocation be a(i,r,t), and remaining useable stock be s(i,r,t). A conceptual objective minimises an explicitly weighted sum of expected expiry losses, late fulfilment, changeover expenditure, energy use and transport burden, subject to capacity, material balance, quality, temperature and contractual constraints. These objectives cannot be replaced by one unexamined cost coefficient; management should expose the Pareto trade-off between service and waste. The solution must also enforce expiry-first dispatch where suitable and prohibit shipping stock with insufficient residual shelf-life. Short-life products may require smaller, more frequent batches even when this reduces nominal line utilisation.

Electricity-aware planning creates several distinct controls. Non-critical cleaning, packaging preparation and flexible pre-cooling may shift within approved thermal limits. Variable-speed motors and equipment maintenance can reduce inefficient consumption. Demand-response participation is rational only after testing quality, recovery time, generator emissions and employee effects. Energy constraints can be added at equipment, line and plant level, with separate models for total kilowatt-hours, peak kilowatts and outages. These metrics reveal why reducing energy per unit does not necessarily reduce maximum transformer loading.

Predictive maintenance contributes if the data link compressor health and plant availability to an actionable service window. IoT and machine-learning applications in food processing provide plausible detection mechanisms [19], but implementation quality and operator expertise determine whether alerts prevent downtime. The optimisation should be fail-safe: loss of connectivity must not disable refrigeration controllers, and plant operators must retain access to a tested manual scheduling procedure. In a disruption scenario, the model should prioritise critical products and safe inventory relocation before nominal cost savings. It should also reflect restoration sequencing because restarting multiple refrigeration compressors simultaneously can impose an electrical peak.

7 Digital distributor coordination and network information rights

The distributor is not merely the final recipient of a finished production plan. It possesses route, retail, cash-flow and expiry information required to distinguish genuine market demand from inventory repositioning. An effective coordination arrangement therefore exchanges time-stamped sell-through, on-hand stock, returns, incoming shipments, forecast overrides and capacity reservations at agreed aggregation levels. Shared interfaces need stable product, batch, location and temperature identifiers. Digital supply-chain research identifies integration and visibility as mediators of operational performance, rather than benefits created automatically by technology purchase [6], [7].

Collaboration should be contractual as well as technical. Manufacturers require sufficient data for planning; distributors need safeguards for commercial confidentiality and competitive information. Access controls can expose reorder quantities and agreed service measures without revealing individual retailer margins. Role-based authorisation, event logging, retention limits and verified data provenance are essential when connecting warehouses, vehicles and manufacturing systems. Shared dashboards should show outstanding alerts, availability-to-promise, ageing inventory and exceptions to agreed service windows. The architecture should keep order acceptance, price changes and unsafe product release behind appropriate human authorisation.

Perishable matching platforms propose linking heterogeneous demand and supply signals across food networks [20], [21]. Their conceptual promise is compelling, but real deployments must resolve missing scans, duplicate transactions, delayed uploads and distributor incentives to overstate projected orders. Blockchain may strengthen traceability where independent parties require a common audit history, yet it does not establish the truth of physical temperature measurements or justify distributed ledger costs for every transaction [22]. A conventional authenticated database may be more reliable when governance is centralised. Digital coordination is successful only when both sides agree how to reconcile disputed inventory and allocate the cost of returns.

Distributor performance should be measured jointly. On-time delivery without product freshness is incomplete, while reducing manufacturer waste by transferring ageing stock to distributors merely relocates loss. Network measures should include final consumer availability, expiry at each custody stage, dwell time, temperature excursions and returns ownership. A transparent gain-sharing mechanism can reward timely sell-through reporting and accurate inventory counts. Supplier collaboration research suggests that information sharing is helpful to resilience, but digital maturity and organisational readiness shape whether the benefit materialises [23]. Contract incentives must therefore reinforce the measurement framework, not compete with it.

8 Sustainable market expansion and network design

Market expansion should follow demonstrated local product-market fit, service economics and cold-chain feasibility. A region with attractive gross demand may be uneconomic once small-drop distribution, returns, refrigeration and cross-docking costs are recognised. Increasing the number of regional stocking points shortens customer lead times but can fragment demand and magnify expiry exposure unless inventory pooling or lateral transfers are permitted.

The international literature connects digital supply-chain coordination with resilience under disruption [8], [24], [25]. It also warns against assuming that highly connected networks are invulnerable: a shared platform or central cold store becomes a concentration risk if there is no offline fallback. Saudi manufacturers should test market entry under motorway delays, customs interruption, heat events and electrical outages. Contingency capacity, alternative wholesalers and reserve packaging suppliers must be valued against the revenue they protect. A network can be efficient in normal conditions yet unviable when the refrigeration node serving several cities fails.

Export readiness adds traceability, destination-specific labelling, quality certification, customs documentation and longer residual shelf-life requirements. Production systems should reserve compliant stock rather than treat export allocation as a last-minute sales override. Sustainable expansion is indicated by improved delivered availability and contribution margin with measured food loss and environmental intensity, not by distribution footprint alone. Smart manufacturing transitions can support this objective when technology, organisational incentives and workforce capability are treated as complementary investments [26], [27].

9 Critical synthesis: Resilience, sustainability and conflicting objectives

Resilience is the capacity to anticipate, absorb, adapt to and recover from disruption rather than the absence of inventory or variation. Empirical and conceptual work links artificial intelligence, data visibility and collaborative capabilities with resilience, while also exposing differences between research settings [8], [9], [28]. Han and colleagues emphasise that resilience metrics have multiple dimensions, preventing a single service indicator from representing network recovery [10]. A robust Saudi evaluation should measure detection delay, recoverable supply, restoration time and unserved critical demand in explicitly described stress scenarios.

There are at least four countervailing effects. Better forecasts may encourage managers to hold less stock, making the network more sensitive to unforeseen disruptions. Centralised allocation may reduce average transport kilometres while creating a single dispatch failure point. Shorter delivery lead times may improve freshness but require additional refrigerated journeys. Finally, artificial intelligence can reduce waste yet increase computational, connectivity and cooling demand. Evidence on digitalisation and energy demand questions blanket efficiency claims [12], while carbon accounting for computation requires transparent assumptions about hardware utilisation and electricity mix [14]. Wider machine-learning climate research emphasises both enabling applications and direct operational costs [13].

The bakery life-cycle assessment is valuable because it compares direct digital-system impacts with avoided product waste [11]. However, the balance depends on the material intensity of the avoided product, the fate of unsold goods and the model's deployment footprint. Food residuals may have uses in feed, digestion or valorisation, but such pathways have different economic and environmental profiles [29]. Reductions in factory disposal alone are an insufficient measure of circularity. Whole-

network accounting should follow ingredients from procurement to final sale or documented recovery route, avoiding double-counting and displacement of losses to distributor balance sheets.

Human-centred resilience adds an ethical boundary. Automated models can privilege high-volume metropolitan markets because their signals are richer and forecast errors cheaper to minimise. Less densely populated regions may experience lower fill rates unless service equity is constrained. Workforce training, explainability and safe escalation processes are necessary, particularly when the algorithm recommends deprioritising a route or shifting a production shift. Supply Chain 5.0 arguments highlight the importance of sustainability and human agency rather than automation as an end in itself [30]. Decision legitimacy requires clear rules on who approves exceptions and how affected partners can challenge the underlying evidence.

Table 2. Balanced decision scorecard for a digitally coordinated Saudi food network.

Dimension	Measure and boundary	Important trade-off	Accountable decision owner
Customer service	Final sell-through fill rate by region	Service versus buffer waste	Sales and distributor lead
Food integrity	Expiry and thermal excursion by custody	Fast dispatch versus cooling load	Quality and cold-chain lead
Production feasibility	Schedule adherence and changeover hours	Utilisation versus flexibility	Factory operations lead
Electrical reliability	Peak kW, critical-load reserve, restoration	Energy cost versus safe temperature	Plant electrical engineer
Resilience	Unserved demand and time to recovery	Efficiency versus redundancy	Network risk committee
Environment and value	Whole-network waste, kWh/kg, net margin	Local gains versus displaced impacts	Sustainability and finance

10 Proposed architecture, governance and implementation pathway

Figure 1 specifies a federated decision architecture in which retailers and distributors contribute verified demand signals; manufacturers retain planning authority; and electrical systems provide independent operational constraints. The data layer performs master-data reconciliation, timestamps, quality checks and consent-sensitive aggregation. A forecasting layer produces calibrated demand distributions across product, city and horizon. A constrained planning layer converts those distributions into feasible batches, allocations and logistics decisions. Physical equipment control remains separate from the analytical platform, with hardwired safety interlocks and validated recovery modes. Feedback from sales, returns, temperatures, energy meters and deviations continuously improves the next planning cycle.

Implementation should proceed in three gated stages rather than a simultaneous enterprise-wide replacement. Stage one establishes data definitions, energy metering, historical baseline accuracy and agreed distributor rights for a limited portfolio. Stage two runs shadow forecasting and scheduling alongside the existing process, recording how recommended decisions would differ without exposing customers to an untested model. Stage three introduces controlled authorisation for selected items and routes, with explicit stop criteria for expiry, safety, forecast bias or electrical overload. Benefits should be assessed using matched products, comparable seasonal periods and

documented commercial interventions. A phased design is compatible with evidence that smart technologies need organisational integration to achieve performance improvements [6].

Figure 2 converts the architecture into a closed accountability cycle. Forecast quality, planning feasibility, service and environmental results should be reviewed at different frequencies. Daily operational meetings resolve shortage and temperature exceptions; weekly reviews analyse forecast bias and distributor stock; monthly governance evaluates energy intensity, service equity, data access and realised net value. A model register records training dates, explanatory limitations, responsible owner and rollback conditions. Cybersecurity exercises should include manipulation of apparent demand and disabling of a distributor interface, not merely standard network availability tests.

An economic case must separate one-off integration costs from recurring subscription, connectivity, sensor calibration and workforce costs. Pilot net value should count avoided expiry, prevented sales losses, inventory carrying cost, refrigeration expenditure and additional distribution cost while excluding benefits not causally attributable to the system. Sensitivity analyses should vary sales-growth assumptions, electricity prices and the quality of distributor participation. The operating framework remains viable only where responsibility for correcting defective data, approving an override and responding to equipment faults is explicit. Organisational readiness, transparency and risk ownership are stronger indicators of scalable value than model complexity alone.

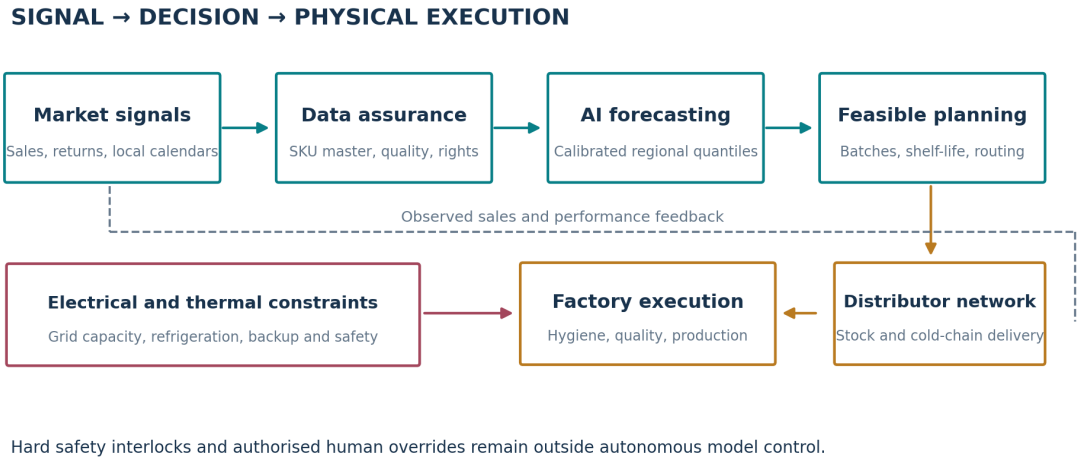

Figure 1. Proposed integrated data, decision and electrical control architecture for Saudi food manufacturing.

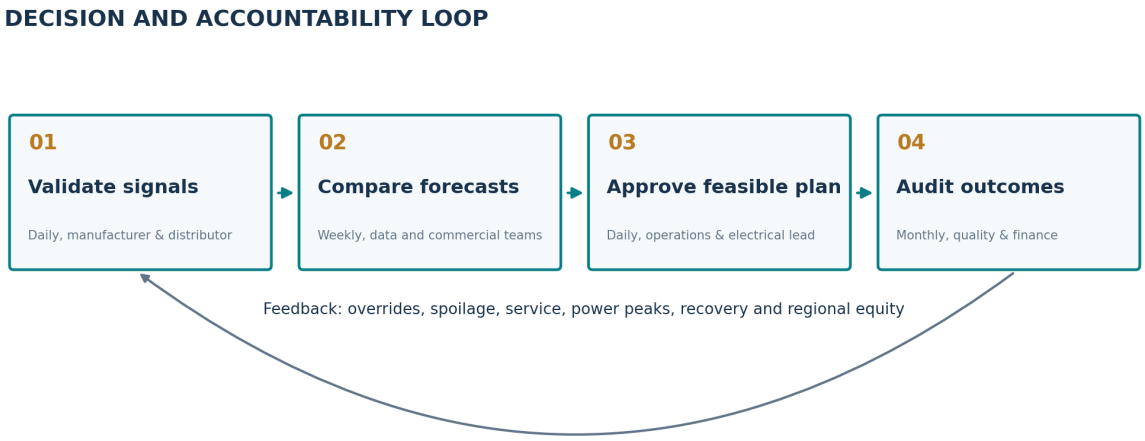

Figure 2. Governance cycle linking forecasts, feasible decisions and measured network outcomes.

11 Research gaps and propositions

Five evidence gaps emerge. First, few evaluations trace probabilistic demand predictions through actual production schedules, distributor movements and final food-loss outcomes. Second, Saudi-specific evidence connecting summertime electrical peaks to product-level scheduling decisions is limited. Third, causal assessments rarely determine whether lower waste in one organisation has been offset by increased returns or disposal elsewhere. Fourth, distributor data-sharing studies insufficiently address bargaining power, privacy and incentives for truthful inventory reporting. Fifth, external validity remains uncertain for secondary Saudi cities, smaller manufacturers and product categories with sparse sales histories.

These gaps generate testable propositions. P1: distributor sell-through sharing improves network service only when identifiers, latency and incentives are jointly governed. P2: calibrated uncertainty forecasts coupled with feasible production optimisation improve the service–waste frontier more consistently than accuracy improvements alone. P3: explicit electrical peak and interruption constraints reduce unsafe or infeasible plans, although they may raise short-run production cost. P4: environmental gains depend on the distribution of waste and energy across the entire network. P5: preserving human override rights improves adoption when override reasons are audited and used to refine future decisions. These are hypotheses requiring prospective evaluation, not findings established by the present review.

12 Future research directions

A priority experiment would enrol multiple Saudi plants and distributor networks representing chilled, frozen and ambient products. Comparable sites could adopt a phased rollout, with pre-specified outcomes and controls for promotions, weather, market growth and supplier disruption. Researchers should publish forecast creation timestamps, available input fields, shelf-life assumptions, and the actual schedules implemented. This would reveal whether forecast improvements survive operational constraints and whether benefits persist outside a highly managed pilot.

A second research stream should combine factory energy submetering with production and cooling digital twins to test demand-response eligibility under real thermal safeguards. Scenarios should include transformer derating, grid interruptions, refrigeration restart peaks and different backup-power arrangements. Carbon accounting should report uncertainty around avoided food production,

electricity mix and refrigerated transport. Work on computation footprints supports tracking the model's own training and inference burden, although it should not obscure larger physical impacts [14].

Third, regional market-expansion models should incorporate service equity and distributor participation as explicit decision variables. Studies can test whether secure aggregation or privacy-preserving analytics improves data availability without revealing sensitive retailer-level information. Independent audits of returns and disposal should establish who captures benefits and who bears transferred costs. Replication with small manufacturers is essential because specialised analysts and sophisticated infrastructure may be absent. Publicly documented benchmark datasets, where commercial rights allow, would support meaningful comparison between simple forecasting, machine learning and human-led scheduling.

13 Conclusion

Intelligent food manufacturing networks are built through disciplined coordination between demand forecasting, safe production, distributor replenishment and electrical infrastructure, not through artificial intelligence in isolation. The reviewed literature supports the usefulness of predictive analytics, integrated visibility and collaborative resilience, while showing that gains are contextual and often mediated by operational decisions [1], [2], [8]. Saudi manufacturers should first repair data definitions and partner incentives, then benchmark uncertainty forecasts, and finally deploy constrained schedules that account for expiry, cooling and power reliability. Commercial expansion should be evaluated against complete network economics and traceable environmental outcomes. The proposed architecture and propositions offer a practical research agenda aligned with Vision 2030, but remain to be tested in Saudi facilities through controlled, multi-site evidence. Greater methodological transparency, service equity and human responsibility will determine whether digitalisation translates into enduring industrial capability and food security.

References

[1] Alquraish, M. (2025). Digital transformation, supply chain resilience, and sustainability: A comprehensive review with implications for Saudi Arabian manufacturing. *Sustainability*, 17, 4495. https://doi.org/10.3390/su17104495

[2] Saryatmo, M.A. and Sukhotu, V. (2021). The influence of the digital supply chain on operational performance: A study of the food and beverage industry in Indonesia. *Sustainability*, 13, 5109. https://doi.org/10.3390/su13095109

[3] Aljuneidi, T., Punia, S., Jebali, A. and Nikolopoulos, K. (2024). Forecasting and planning for a critical infrastructure sector during a pandemic: Empirical evidence from a food supply chain. *European Journal of Operational Research*, 317, 936–952. https://doi.org/10.1016/j.ejor.2024.04.009

[4] Makridakis, S., Spiliotis, E. and Assimakopoulos, V. (2022). M5 accuracy competition: Results, findings, and conclusions. *International Journal of Forecasting*, 38, 1346–1364. https://doi.org/10.1016/j.ijforecast.2021.11.013

[5] Lim, B., Arık, S.Ö., Loeff, N. and Pfister, T. (2021). Temporal Fusion Transformers for interpretable multi-horizon time series forecasting. *International Journal of Forecasting*, 37, 1748–1764. https://doi.org/10.1016/j.ijforecast.2021.03.012

[6] Nasiri, M., Ukko, J., Saunila, M. and Rantala, T. (2020). Managing the digital supply chain: The role of smart technologies. *Technovation*, 96–97, 102121. https://doi.org/10.1016/j.technovation.2020.102121

[7] Reaidy, P., Alaeddini, M., Gunasekaran, A., Lavastre, O. and Shahzad, M. (2024). Unveiling the impact of Industry 4.0 on supply chain performance: The mediating role of integration and visibility. *Production Planning & Control*. https://doi.org/10.1080/09537287.2024.2440454

[8] Zamani, E.D., Smyth, C., Gupta, S. and Dennehy, D. (2023). Artificial intelligence and big data analytics for supply chain resilience: A systematic literature review. *Annals of Operations Research*, 327, 605–632. https://doi.org/10.1007/s10479-022-04983-y

[9] Spieske, A., Gebhardt, M., Kopyto, M., Birkel, H. and Hartmann, E. (2023). The future of Industry 4.0 and supply chain resilience after the COVID-19 pandemic: Empirical evidence from a Delphi study. *Computers & Industrial Engineering*, 181, 109344. https://doi.org/10.1016/j.cie.2023.109344

[10] Han, Y., Chong, W.K. and Li, D. (2020). A systematic literature review of the capabilities and performance metrics of supply chain resilience. *International Journal of Production Research*, 58, 4541–4566. https://doi.org/10.1080/00207543.2020.1785034

[11] Hübner, N., Caspers, J., Coroamă, V.C. and Finkbeiner, M. (2024). Machine-learning-based demand forecasting against food waste: Life cycle environmental impacts and benefits of a bakery case study. *Journal of Industrial Ecology*, 28, 1117–1131. https://doi.org/10.1111/jiec.13528

[12] Lange, S., Pohl, J. and Santarius, T. (2020). Digitalization and energy consumption: Does ICT reduce energy demand? *Ecological Economics*, 176, 106760. https://doi.org/10.1016/j.ecolecon.2020.106760

[13] Rolnick, D., Donti, P.L., Kaack, L.H. et al. (2022). Tackling climate change with machine learning. *ACM Computing Surveys*, 55, 42. https://doi.org/10.1145/3485128

[14] Lannelongue, L., Grealey, J. and Inouye, M. (2021). Green Algorithms: Quantifying the carbon footprint of computation. *Advanced Science*, 8, 2100707. https://doi.org/10.1002/advs.202100707

[15] Wang, L., Deng, T., Shen, Z.-J.M., Hu, H. and Qi, Y. (2022). Digital twin-driven smart supply chain. *Frontiers of Engineering Management*, 9, 56–70. https://doi.org/10.1007/s42524-021-0186-9

[16] Lim, B. and Zohren, S. (2021). Time-series forecasting with deep learning: A survey. *Philosophical Transactions of the Royal Society A*, 379, 20200209. https://doi.org/10.1098/rsta.2020.0209

[17] Principato, L., Marchetti, S., Barbanera, M., Ruini, L., Capoccia, L., Comis, C. and Secondi, L. (2023). Introducing digital tools for sustainable food supply management: Tackling food loss and waste in industrial canteens. *Journal of Industrial Ecology*, 27, 1060–1075. https://doi.org/10.1111/jiec.13391

[18] Jackson, I., Namdar, J., Sáenz, M.J., Elmquist, R.A. III and Dávila Novoa, L.R. (2025). Revolutionize cold chain: An AI/ML driven approach to overcome capacity shortages. *International Journal of Production Research*, 63, 2190–2212. https://doi.org/10.1080/00207543.2024.2398583

[19] Kumar, I., Rawat, J., Mohd, N. and Husain, S. (2021). Opportunities of artificial intelligence and machine learning in the food industry. *Journal of Food Quality*, 2021, 4535567. https://doi.org/10.1155/2021/4535567

[20] Birkmaier, A., Imeri, A., Riester, M. and Reiner, G. (2023). Preventing waste in food supply networks: A platform architecture for AI-driven forecasting based on heterogeneous big data. *Procedia CIRP*, 120, 708–713. https://doi.org/10.1016/j.procir.2023.09.063

[21] de Vass, T., Shee, H. and Miah, S.J. (2021). IoT in supply chain management: A narrative on retail sector sustainability. *International Journal of Logistics Research and Applications*, 24, 605–624. https://doi.org/10.1080/13675567.2020.1787970

[22] Rejeb, A., Keogh, J.G., Zailani, S., Treiblmaier, H. and Rejeb, K. (2020). Blockchain technology in the food industry: A review of potentials, challenges and future research directions. *Logistics*, 4, 27. https://doi.org/10.3390/logistics4040027

[23] Zouari, D., Ruel, S. and Viale, L. (2021). Does digitalising the supply chain contribute to its resilience? *International Journal of Physical Distribution & Logistics Management*, 51, 149–180. https://doi.org/10.1108/IJPDLM-01-2020-0038

[24] Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak case. *Transportation Research Part E: Logistics and Transportation Review*, 136, 101922. https://doi.org/10.1016/j.tre.2020.101922

[25] Belhadi, A., Kamble, S., Jabbour, C.J.C., Gunasekaran, A., Ndubisi, N.O. and Venkatesh, M. (2021). Manufacturing and service supply chain resilience to the COVID-19 outbreak: Lessons learned from the automobile and airline industries. *Technological Forecasting and Social Change*, 163, 120447. https://doi.org/10.1016/j.techfore.2020.120447

[26] Sarkar, B.D., Shardeo, V., Dwivedi, A. and Pamucar, D. (2024). Digital transition from Industry 4.0 to Industry 5.0 in smart manufacturing: A framework for sustainable future. *Technology in Society*, 78, 102649. https://doi.org/10.1016/j.techsoc.2024.102649

[27] Chauhan, S., Singh, R., Gehlot, A., Akram, S.V., Twala, B. and Priyadarshi, N. (2023). Digitalization of supply chain management with Industry 4.0 enabling technologies: A sustainable perspective. *Processes*, 11, 96. https://doi.org/10.3390/pr11010096

[28] Belhadi, A., Mani, V., Kamble, S.S., Khan, S.A.R. and Verma, S. (2024). Artificial intelligence-driven innovation for enhancing supply chain resilience and performance under the effect of supply chain dynamism: An empirical investigation. *Annals of Operations Research*, 333, 627–652. https://doi.org/10.1007/s10479-021-03956-x

[29] Said, Z., Sharma, P., Quynh, T.B.N., Bora, B.J. et al. (2023). Intelligent approaches for sustainable management and valorisation of food waste. *Bioresource Technology*, 377, 128952. https://doi.org/10.1016/j.biortech.2023.128952

[30] Frederico, G.F. (2021). From Supply Chain 4.0 to Supply Chain 5.0: Findings from a systematic literature review and research directions. *Logistics*, 5, 49. https://doi.org/10.3390/logistics5030049