Digital Transformation of Petroleum Retail Operations: A Framework for Enhancing Operational Efficiency and Sustainability in Saudi Arabia.

Abstract

Retail fuel outlets are increasingly expected to deliver reliable, convenient and environmentally responsible services while managing volatile demand, complex assets and growing volumes of transactional data. This review evaluates how digital transformation can improve operational efficiency and sustainability in Saudi Arabian petroleum retailing. It integrates evidence from fuelstation automation, connected inventory control, logistics optimisation, customerfacing services, energy management and environmental monitoring, while distinguishing findings established at service stations from those inferred from wider oilandgas or digitalbusiness research. The analysis develops an operating framework linking connected forecourt assets and enterprise systems to governed decision processes, measurable service outcomes and environmental safeguards. Its central argument is that isolated technology deployments are insufficient: performance gains depend on accurate measurement, interoperable data, worker capability, operational redesign and disciplined evaluation. A transparent illustrative stationlevel assessment demonstrates how operational, financial and environmental indicators can be combined without conflating scenario assumptions with observed effects. The review proposes a staged implementation and evaluation agenda suitable for different scales of Saudi fuelretail networks and identifies the empirical evidence required before claims of national applicability can be made.

Keywords: Petroleum retail; digital transformation; service stations; operational efficiency; energy management; inventory reconciliation; Saudi Arabia; sustainability.

1. Introduction

Saudi Arabia's network of petroleum retail outlets forms a consumerfacing part of the energy system, yet its operational problems differ markedly from those of exploration, refining and large pipeline infrastructure. At station level, economic performance depends on the integrity of fuel measurement, pump availability, tanker delivery coordination, transaction speed, staffing, conveniencestore operations and customer confidence. Environmental performance likewise arises from practical activities: electricity consumed by forecourt equipment and refrigeration, loss prevention, vapour controls, wastewater management, safe storage and wellmaintained infrastructure. These concrete activities provide a more useful unit of analysis than treating the entire petroleum value chain as a single digitalisation problem. Research on the wider Gulf oil and gas industry establishes the strategic importance of digital capability,but does not itself demonstrate the financial benefits of digital systems in Saudi retail outlets (AlHajri et al., 2024).

Digital transformation is not synonymous with buying connected sensors or moving accounting records to a cloud service. It involves changes in the organisation's capacity to sense operational events, interpret information and alter decisions or routines in response. Vial (2019) identifies organisational change and competing outcomes as integral to digital transformation, while Verhoef et al. (2021) distinguish digitisation of information from broader changes in value creation. Applied to a fuel station, this means that live tank telemetry becomes economically relevant only when alerts lead to improved ordering decisions, abnormalstock investigations or preventive interventions. Similarly, digital payments are operationally meaningful if they reduce transaction friction without weakening control over refunds, reconciliation or consumer data.

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The Saudi policy context adds incentives for efficiency, industrial modernisation and responsible resource use. Yusuf and Lytras (2023) consider digitalisation alongside the circular carbon economy in Saudi business strategy; Alsuhaibany (2025) presents evidence of complementary relationships between digital innovation, resource efficiency and sustainability within the national oil and gas sector. Both help establish contextual plausibility, but neither isolates retail station performance. Evidence from retailspecific studies therefore deserves greater weight when drawing operational conclusions, particularly where customer demand, physical infrastructure and safety requirements create a distinctive risk profile. A further challenge is that benefits in one country may not transfer directly to Saudi Arabia because tariffs, business formats, service routines, labour arrangements and infrastructure maturity differ.

The paper addresses the question: under what organisational, technical and environmental conditions can digitally connected petroleum retail operations produce defensible improvements in efficiency and sustainability? Its aim is to develop a decisionoriented framework that makes the link between technology adoption and verified station performance explicit. Four objectives guide the review: to identify operational mechanisms across the retail value chain; to compare measures suitable for assessing efficiency, resilience and environmental exposure; to examine governance and workforce conditions affecting implementation; and to construct a staged assessment model relevant to Saudi network operators. Unlike a generic survey of oilindustry technologies, the analysis maintains the service station as its principal operational boundary.

2. Review design and analytical approach

A structured integrative review was selected because the relevant evidence spans disparate study designs: conceptual accounts of transformation, prototype fuelpump systems, applied servicestation experiments, supplychain optimisation models and environmental field measurements. This heterogeneity makes a pooled average treatment effect inappropriate. The review instead uses analytical comparison and mechanism tracing: for each source, it distinguishes the intervention, operating context, reported outcome, methodological boundary and degree of transferability to Saudi fuel retailing. Studies dealing only with upstream asset production or generic digital transformation were retained for theoretical insight rather than used to estimate stationlevel effects. This distinction avoids a common category error in sector reviews, where a finding from refinery optimisation is described as though it were measured at retail dispensers.

The publication window was limited to 2015–2025. The evidence base was assembled through targeted searches of scholarly publisher records and bibliographic indexes, complemented by citation checking and the three supplied Saudi and Gulf studies. Search concepts included petroleum or fuel retail, service station, Internet of Things, automation, retail network strategy, replenishment routing, vapour emissions, digital twins, operational efficiency and sustainability. Sources were retained when their bibliographic identity and DOI could be matched to a discoverable publisher or index entry and their substantive contribution was relevant to at least one component of the framework. This is a focused, reproducible narrative synthesis, not an exhaustive database census; no fictitious screening totals, effect sizes or pooled statistical estimates are reported.

Each article was coded conceptually against five evidence domains: station operations and instrumentation; inventory and distribution; customer service and commercial strategy; environmental and occupational safeguards; and organisational capabilities. A second coding dimension separated direct stationbased evidence from other petroleumindustry studies, crosssector business research and engineering feasibility designs. The third dimension classified outcomes as observed, simulated, proposed or contextual. Thus, an engineered RFID system is evidence of technical feasibility rather than proof of workforce savings; a route optimisation paper demonstrates model behaviour under stated constraints rather than assured savings across all Saudi distribution networks. Quantitative values are reproduced only where their meaning and population can be stated clearly.

The review acknowledges several unavoidable limitations. Search results may favour Englishlanguage and digitally indexed publications, and the availability of stationlevel proprietary data is especially constrained.

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Several systems papers report prototypes without longitudinal operation, while published sustainability measurements differ in geography, fuel formulation and regulatory exposure limits. Accordingly, the framework is proposed as an analytical and managerial tool requiring validation, not an empirically established nationwide effect. Numerical operating scenarios are labelled as hypothetical, their assumptions are disclosed, and no Saudi company is presented as the source of fabricated data. This treatment is consistent with the broader literature's emphasis on organisational context and evidence quality (Hanelt et al., 2021; Kraus et al., 2022).

3. Petroleum retail as an integrated operating system

A forecourt is a tightly coupled combination of physical metrology, logistics, payment infrastructure, customer interaction and risk management. Fuel enters through scheduled deliveries, is held in underground or aboveground tanks, passes through calibrated dispensers and becomes a financial transaction. Discrepancies between physical and accounting quantities can stem from timing differences, temperature effects, imperfect measurement, delivery recording errors or actual loss. Digital integration should therefore begin with a carefully defined reconciliation boundary, common time stamps, verified sensor calibration and accountable exception handling. Merely displaying a level gauge on a remote dashboard does not establish accurate stock integrity. The most valuable technical architecture is one that preserves traceability from a delivery document through tank movement to dispenser totalisers and recorded sales.

Retail operations also encompass maintenance, staff scheduling and conveniencestore performance. A failed dispenser can alter queue length and customer choice; a refrigeration fault can damage nonfuel inventory; an incomplete shift handover can delay resolution of a safety incident. Connected instruments can help identify such problems earlier, but only if alarms are prioritised and frontline workers retain clear authority to act. Frank et al. (2019) show that introducing foundational digital technologies often lags more visible operational applications, while Bai et al. (2020) emphasise that sustainability appraisal must include social and environmental effects alongside productivity. These findings suggest that a petrol retailer should assess information integrity, staff workload and compliance risk as seriously as transaction throughput.

The commercial proposition is also changing. Panduru and Scarlat (2022), drawing on interviews in Romanian fuel networks, identify the development of convenience retail, alternative fuels, connected services and digital customer interaction as major strategic directions. These findings cannot establish Saudi consumer preferences, but they show why a retail transformation cannot be assessed exclusively through litres dispensed. Fuelmargin management, nonfuel basket size, service availability, repeat visits and dwell time may respond differently to a technology. For example, a payatpump interface can shorten payment time while limiting exposure to the shop; the resulting tradeoff must be evaluated using stationspecific transaction patterns rather than assuming every form of automation raises total gross profit.

This operational perspective supports three nested performance boundaries. At the asset level, operators monitor availability, faults, maintenance intervention and metrological integrity. At the site level, they monitor labour effort, customer waiting, electricity, reconciled stock and nonfuel sales. At the network level, they monitor replenishment reliability, crosssite benchmarking, cybersecurity exposure and portfolio investment returns. Data collected at one level should not automatically be converted into a performance claim at another. A network average, for example, may disguise a profitable highway outlet and a lowvolume neighbourhood station whose optimal digital configuration differs substantially.

4. Digital technologies and the mechanisms of improvement

Connected tank gauges, dispenser controllers and environmental sensors create the data foundation for stationlevel optimisation. Marques et al. (2021) examined a servicestation conveniencestore setting using Bluetoothbased sensing and enterprise data, illustrating how local observations can inform operational interpretation. Baqir and Motlak (2021) present RFID and WiFibased pump monitoring, while their subsequent technical chapter elaborates a connected dispensing concept with protected data exchange (Baqir & Motlak,

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2023). These studies establish implementable configurations, not universal estimates of customer waitingtime reduction or business profitability. For deployment at scale, technical criteria must extend beyond connectivity to calibration, interoperability, maintainability, audit logs, cybersecurity and the availability of safe manual fallback procedures.

Recent prototype studies further illustrate the possibilities and boundaries of automating retail tasks. Sugumaran et al. (2024) connect fuellevel, equipmentstatus and transaction signals to remote management, whereas Jemat et al. (2024) describe a progressive web application coupled to a simulated pump interface. In the latter case, the principal contribution is feasibility and interface design; measured longterm station performance was not established. Device selection alone is therefore a poor procurement metric. An evaluation should instead ask whether the installation produces complete data across delivery, sale and inventory events; whether it detects actionable exceptions with acceptable false alarms; and whether maintenance staff can troubleshoot failed links without disabling critical protective equipment.

A reliable architecture needs separation between operational technology and customerfacing information systems. Pump authorisation and emergency shutdowns must remain subject to certified controls, while cloud dashboards and mobile applications should have carefully limited privileges. A layered approach can place local acquisition near the forecourt, validate readings at an integration gateway, reconcile transactions centrally and then generate decisionsupport outputs. Realtime or nearrealtime processing should be justified by the decision cadence: leak alarms demand immediate escalation, stock replenishment may require hourly updates, and capital budgeting may use monthly summaries. Cloud and edge analyses in the wider energy sector emphasise that the tradeoffs include network dependence, privacy and resilience as well as raw processing capability (Knebel et al., 2023).

Predictive models can support dispenser maintenance, stock demand and delivery planning. However, their value depends on a known decision threshold and a credible comparison with simpler baselines. A complex model is not necessarily superior to thresholdbased alarms for equipment faults if failures are rare and maintenance histories are incomplete. The broader digital twin literature indicates that realistic data acquisition, model validation and operational integration remain significant barriers even for larger oilandgas assets (Wanasinghe et al., 2020; Meza et al., 2024). For a station, a modest conditionmonitoring model with transparent escalation may therefore be more defensible than a visually sophisticated virtual replica lacking validated physical parameters.

Replenishment is a particularly attractive optimisation problem because it combines stockout risk, delivery capacity and transport cost. Assahla et al. (2021) discuss artificialintelligence approaches to planning station deliveries, whereas Haseltalab and Karimi (2025) explicitly model multicompartment vehicles and evaporative losses. Such models may improve dispatch choices under defined assumptions, but operational adoption also requires reliable inventory telemetry, driver constraints, delivery access windows and emergency stock policies. High forecast accuracy does not guarantee good replenishment performance when route decisions ignore actual unloading times or changing traffic conditions. Network operators should therefore evaluate avoided stockouts, delivered litres per kilometre, missed delivery windows and servicelevel resilience together, rather than judging the system solely by a model’s objectivefunction improvement.

Customerfacing technologies require a separate evidence chain. Payment applications, fleetaccount authorisation, digital receipts and loyalty systems can reduce paperwork and increase traceability, but they also create risks relating to fraud, downtime and personal information. Retail network research supports the importance of convenience and service diversification (Panduru & Scarlat, 2022), but evidence for a particular Saudi demographic must be collected locally. A pilot should distinguish registered users from active users, measure payment completion and error rates, and estimate whether transactions simply move from counter to dispenser or genuinely reduce total service time. A credible analysis also records cases in which the digital interface fails and staff must intervene.

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5. From digital records to verifiable operational outcomes

Operational efficiency is a ratio or comparison that must specify what is being consumed and what output is generated. A fall in time per transaction, for example, may be offset by extra exception handling or slower settlement reconciliation. Likewise, a reduction in fuel inventory variance is valuable as a control improvement but does not demonstrate equivalent savings in purchased fuel unless the cause of variance is identified. Four indicator families are therefore recommended: control integrity, service reliability, resource productivity and customer experience. Each indicator requires an unambiguous formula, unit, baseline and collection frequency. Crossfunctional governance prevents the same improvement from being claimed simultaneously by finance, logistics and operations as separate financial benefits.

Stock reconciliation is a particularly useful test of whether digital integration has moved beyond dashboard production. A daily reconciliation can compare opening inventory plus verified receipts less closing inventory with metered sales, adjusting for known measurement conditions and authorised corrections. Exception rates may be reported as a proportion of handled fuel volume, with investigation categories assigned after inspection. A digital system can make discrepancies more visible without reducing them immediately; this should be interpreted as improved detection rather than operational deterioration. Conversely, a sudden decline in alerts following system configuration may reflect changed reporting thresholds, not better control. Such measurement discipline is crucial when a network is considering investments in remote tank monitoring.

Maintenance measures should combine asset uptime with intervention effectiveness. Available minutes, fault recurrence, mean time to restoration and workorder closure quality provide a stronger picture than raw alert counts. Alerts should be linked to equipment identification, service logs and actual faults so that false positive rates can be audited. The general oilandgas digital twin literature points toward condition monitoring and assetintegrity applications (Ghenai et al., 2022; Wanasinghe et al., 2020), but retail operators need to validate these methods using dispenser, compressor, lighting, paymentterminal and refrigeration failure modes. An algorithm that performs well on pipeline degradation will not automatically predict retail equipment failure.

A second crucial distinction concerns the difference between operational outcomes and commercial returns. The additional sales created by higher pump availability should be measured in gross contribution, not gross revenue, and only when demand would otherwise have been lost rather than displaced to another pump or time period. Labour hours released by automation have economic value only if staffing costs decline or productive work expands. Similarly, lower electricity consumption produces cash savings only after tariff and operatinghour assumptions are checked. Kamble and Gunasekaran (2020) stress the need for suitable performance measurement architectures, while Bag et al. (2020) show why analytics outcomes must be interpreted through organisational capabilities. The illustrative tables below apply these principles rather than assigning general percentage gains to Saudi operators.

Data quality may itself become an operational outcome. A network can measure the percentage of dispenser transactions successfully matched with payment records, the share of deliveries with complete electronic proof, sensor uptime and unresolved exceptions older than a defined threshold. These leading indicators connect directly to staff confidence in digital reports. If two departments still maintain conflicting item codes or time bases, adding sophisticated visual analytics may simply automate contradictory conclusions. Organisational research therefore matters even for technically modest installations: digital transformation proceeds through continuing adjustments in work, authority and data stewardship, not a single implementation event (Hanelt et al., 2021; Kraus et al., 2021).

6. Sustainability and occupational protection in petroleum retail

Environmental sustainability at a petrol station is operationally specific and must be interpreted separately from the carbon footprint of fuel ultimately combusted by customers. Electricity consumed on site, generator use, fugitive vapour releases, fuel spills, water management and equipment replacement are directly or partially controllable through station practices. Smart lighting controls and equipment scheduling may reduce

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purchased electricity; leak and abnormalstock alerts may shorten the time to inspection; improved maintenance may extend useful equipment life. None of these sitelevel changes, however, should be represented as eliminating the lifecycle emissions associated with the petroleum products sold. Yusuf and Lytras (2023) frame digitalisation as an enabling capability for circularcarbon strategies, a useful perspective provided the accounting boundary remains explicit.

Vapour emissions are especially important because gasoline handling produces volatile organic compounds and potential worker exposure. Zeng et al. (2022) measured species patterns and associated risks at a service station in China, including exceedances at some sampling points despite existing controls. Hu et al. (2023) investigated vapourcontrol streams at service stations in Beijing and identified implications for secondary pollution. At the distribution interface, Liang et al. (2024) examined a recovery configuration for gasoline depots, demonstrating why upstream loading controls can complement—not replace—retailsite safeguards. These studies support the need for systematic vapourcontrol maintenance and monitoring, but climatic conditions, fuel composition, equipment configuration and regulatory criteria prevent simple transfer of their concentration values to Saudi outlets. The priority is to maintain tested hardware, document inspection and operating conditions, and use sensing to support—not replace—appropriate occupational and environmental assessment.

Evidence from international employeeexposure studies illustrates the value of interventions while reinforcing the need to distinguish context. Shinohara et al. (2025) report lower estimated employee risks in stations equipped with vapour recovery than in those without it under the study conditions. This should not be rewritten as a forecast reduction for Saudi workers. Moreover, the implementation chain involves practical human factors: staff need to recognise damaged hoses and malfunctioning recovery systems, supervisors must close work orders, and qualified personnel must maintain equipment. A digital incident log improves accountability only when its entries trigger timely physical remediation. It is equally important to avoid treating the absence of an automated alert as evidence that exposure is acceptably low.

Other sustainability opportunities connect the forecourt to an evolving mobility system. Shah et al. (2023) assessed photovoltaics linked to charging infrastructure at existing fuel stations across three Pakistani cities and reported locationspecific levelised electricity cost estimates. These are useful engineering comparisons, not Saudi investment prices. A Saudi station feasibility assessment would require its own solar irradiation, shade, roof strength, grid connection, electricity tariff, charger demand, firesafety arrangements and landuse constraints. The strategic case may depend as much on customer dwell time and retail service adaptation as on electricity unit costs. Panduru and Scarlat (2022) show that fuel networks are already considering a broader portfolio of services, but investment sequencing must reflect local demand and the site’s actual capacity.

The environmental performance of a retail network also includes indirect impacts arising from distribution. Forecastdriven tanker routing may reduce empty vehicle movements or unnecessary emergency deliveries, but should be evaluated alongside fuel availability and safety. Models that include evaporation or product deterioration, such as Haseltalab and Karimi (2025), demonstrate how optimisation objectives can capture more than distance. Jabbour et al. (2020) argue for digitally enabled sustainability assessment across supply chains; at retail level, that logic supports consistent definitions for product losses, freight emissions and supplier performance. The boundary should include outsourced transport where the retailer can influence delivery decisions, while disclosing emissions sources that remain outside direct management control.

A credible sustainability dashboard therefore needs multiple safeguards. First, data should be attributed to a specific physical site and period rather than aggregated without context. Second, units and conversion factors must be documented, including whether electricity is measured or allocated. Third, performance changes should be normalised for throughput, ambient temperature and trading hours where appropriate. Fourth, occupational incidents and near misses should not be suppressed in pursuit of attractive headline indicators. Finally, benefits must be weighed against the resource and cybersecurity costs of additional equipment. Bai et

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al. (2020) and Alsuhaibany (2025) provide broader support for integrating operational and environmental dimensions, although only a measured local intervention can validate a specific net benefit.

7. An integrated transformation framework for Saudi retail networks

The proposed framework comprises five linked layers, illustrated in Figure 1. The physical layer includes dispensers, tanks, delivery interfaces, payment terminals, energy meters and relevant environmental controls. The integration layer preserves event time, asset identity, calibration status and secure data transfer. The intelligence layer reconciles inventory, identifies anomalies, predicts demand and supports maintenance prioritisation. The decision layer assigns clear responsibilities to forecourt employees, maintenance teams, distributors and network managers. The outcome layer evaluates service reliability, control accuracy, financial contribution, worker protection and environmental performance. The arrows connecting these layers represent accountable work processes rather than an assumed technological causal effect. A continuous feedback mechanism updates operating rules using verified results.

The model is deliberately modular. A small independent operator may prioritise electronic daily reconciliation, pump health visibility and a secure payment interface. A multisite operator may add crossstation benchmarking, route planning, common maintenance records and portfolio investment controls. Neither architecture should bypass safetycertified equipment or undermine the availability of offline operations. Hanelt et al. (2021) describe digital transformation as organisational adaptation, a principle reinforced in retail by the need for local accountability. Standardised information is useful only when it is paired with roles, audit processes and incentives that reward accuracy rather than optimistic reporting.

Four design principles follow. The first is to maintain a physicaltofinancial chain of evidence from delivered litres to reconciled sales. The second is to match analytics latency to the decision: milliseconds matter in safety shutdowns, but not necessarily in stock forecasts or sustainability reporting. The third is to preserve a human override and incident pathway for safetycritical activities. The fourth is to evaluate each proposed feature against a measurable counterfactual, ideally comparing sites with similar demand and equipment conditions over a representative period. Without these safeguards, a digital rollout risks measuring software use rather than genuine operational change.

The framework also places governance around data ownership and interoperability. Procurement specifications should require documented interfaces, accessible exports, service records and cybersecurity responsibilities so that network operators do not become unable to audit their own operating data. Hardware suppliers and software vendors may each report a different definition of uptime; contract terms should therefore fix a common measurement basis. Retail customer records require separate treatment from equipment telemetry, with minimal access privileges and documented retention rules. The wider energy literature identifies cloud and edge deployment complexity as a challenge (Knebel et al., 2023), reinforcing the merit of testing connectivity failures, delayed synchronisation and practical recovery before a system is scaled.

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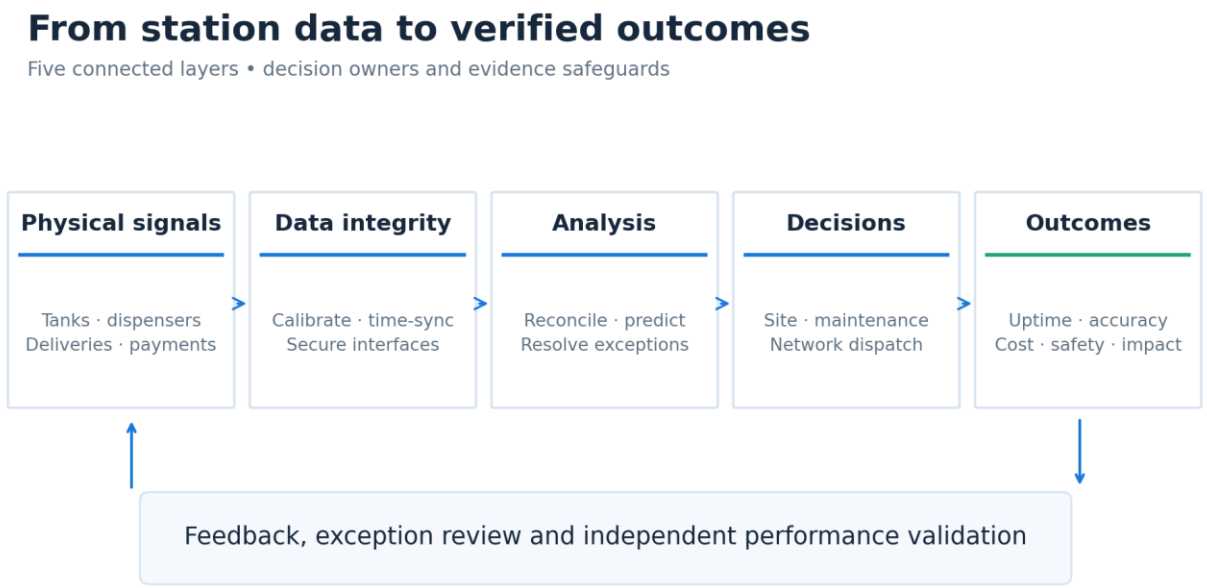


Figure 1. Integrated physicaltodecision framework for petroleum retail operations (authordeveloped synthesis).

8. Quantitative interpretation and evaluation design

Table 1 provides selected numerical findings from studies whose populations and denominators are identifiable. The values are intentionally not pooled. In particular, the 505 documents analysed by AlHajri et al. (2024) describe a regional research corpus; the 348 survey responses analysed by Alsuhaibany (2025) describe executives in the Saudi oil and gas sector; neither figure represents the number of fuel outlets evaluated. Likewise, station exposure and route optimisation results come from their respective international research designs. Presenting such evidence together highlights the richness of the field while preventing a false impression that a standard percentage efficiency gain has been measured for Saudi retail networks.

Table 2 converts the conceptual model into operational indicators suitable for a prospective pilot. Values are deliberately illustrative. They describe a hypothetical outlet handling 24,000 litres per day, not a recorded Saudi company or a statistically estimated baseline. The indicators encompass both leading measures—such as complete sales matching—and lagging outcomes such as fault downtime and electricity use. The analysis treats differences between columns as targets or scenarios to be tested, not results achieved. Each improvement needs a measurement plan: common periods, recording rules, weather or demand controls, and an explicit response procedure for missing data. Figure 2 visualises the same example in relative form so that unlike units are not mistaken for directly comparable economic benefits.

Table 3 then specifies a separate indicative financial logic. Its figures illustrate the importance of avoiding double counting. Reduced task hours have a value only where hours can be redeployed productively or purchased hours avoided; lower downtime contributes to margin only where sales are truly incremental; lower energy purchases depend on the site’s tariff; and reduced conveniencestore spoilage depends on accountable cost of goods sold. The example has positive gross benefits, but recurring support and initial installation cost materially change payback. The figures should be replaced with observed quotations, contracts and validated operational data before any investment decision. The reconciliation variance example is intentionally excluded from cash savings because a smaller accounting discrepancy is not itself a verified physical recovery of product.

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Sensitivity analysis is necessary because the economics of a small neighbourhood station may differ considerably from those of a highvolume forecourt. Table 4 holds the proposed onetime investment constant while varying annual gross benefits and recurring digital support cost. The resulting simple payback is an arithmetic scenario, not a forecast: it excludes discounting, financing, tax effects and any unquantified worker or environmental gains. Its purpose is to expose the conditions under which a business case would change materially. An operator should also test upside and downside exposure from systems outages, cyber incidents and the risk that a pilot's apparent gains reflect unusual trading conditions rather than the intervention.

The most defensible future research design would employ a staggered multisite deployment with prespecified indicators and matched comparison stations. At least one full seasonal demand cycle would improve interpretation where temperatures, holiday travel and trading patterns affect outcomes. For operational timeseries indicators, a differenceindifferences or interrupted timeseries design may be suitable when paralleltrend and measurement assumptions are evaluated. Safety indicators may need eventbased qualitative review because rare events are not adequately assessed through monthly averages alone. Researchers should publish site selection, attrition, instrumentation accuracy, missingness, data processing and cost boundaries, rather than reporting only positive changes after implementation.

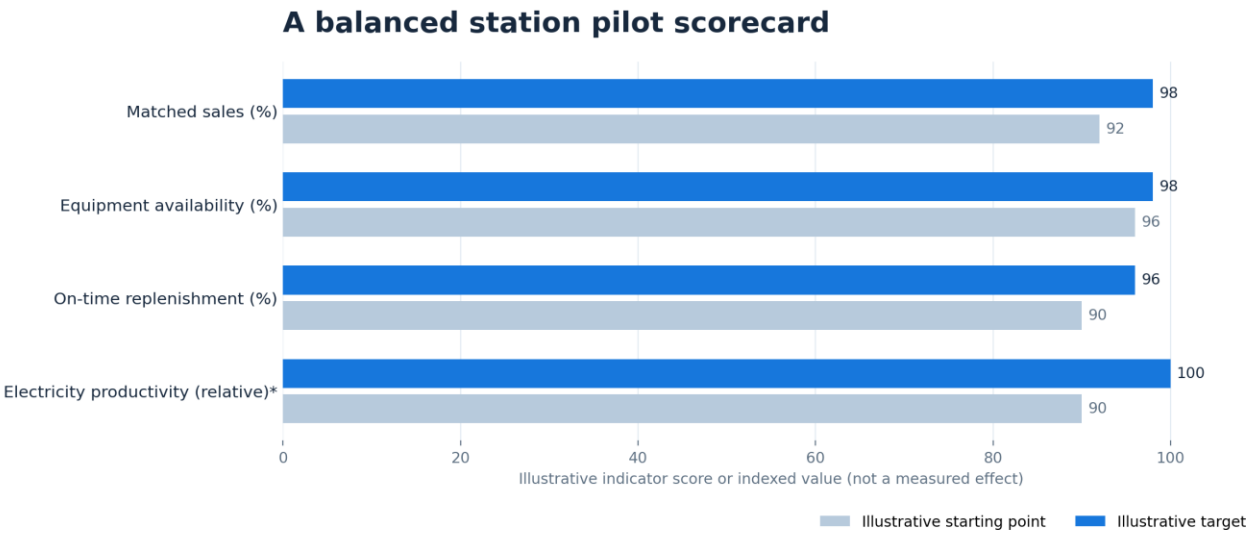
Table 1. Selected numerical findings and boundaries in the evidence base

Study / setting	Numerical finding	How it should be interpreted
AlHajri et al. (2024), GCC O&G review	505 documents analysed	Research publications, not Saudi retail stations
Alsuhaibany (2025), Saudi O&G	348 executive survey responses	Sectorlevel associations, not station effect size
Zeng et al. (2022), Chinese station	24% of boundary samples exceeded reference	Sitespecific pollutant measurements
Shinohara et al. (2025), Mexico	47–61% lower estimated risk with recovery	International workerexposure study
Shah et al. (2023), Pakistan	3.85–4.07 US¢/kWh modelled LCOE	Citydependent solarcharging feasibility
Haseltalab & Karimi (2025), route model	4.45% gap in bestknown solution	Algorithm comparison, not observed cash saving

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Table 2. Illustrative operating scorecard for a single station

Indicator (unit)	Starting point	Target scenario	Definition / measurement rule
Sales matched to receipts (%)	92.0	98.0	Successfully reconciled / total transactions
Dispenser availability (%)	96.0	98.0	Available operating time / scheduled time
Ontime fuel deliveries (%)	90.0	96.0	Receipts inside agreed delivery window
Inventory exception rate (%)	0.30	0.15	Unexplained absolute variance / litres handled
Electricity use (MWh/year)	240	216	Metered annual station consumption
Manual reconciliation (hours/day)	2.0	0.9	Staff tasktime sampling



*Electricity productivity: 90 → 100 is an illustrative index; all four measures have separate denominators.

Figure 2. Selected illustrative indicators; plotted values are not observations from Saudi stations.

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Table 3. Illustrative financial logic: annual station operating case

Benefit channel	Assumption and calculation	Value (SAR/year)
Reconciliation time	1.1 hours/day × 365 × SAR 50/hour	20,075
Avoided lost contribution	8 avoided downtime hours × SAR 800/hour	6,400
Lower electricity purchases	24,000 kWh × SAR 0.20/kWh	4,800
Nonfuel spoilage reduction	0.6% × SAR 1,200,000 COGS	7,200
Gross annual illustrative benefit	Sum of the four channels	38,475
Recurring digital platform & upkeep	Annual support and maintenance allowance	(12,000)
Net annual indicative benefit	Gross less recurring outlay	26,475
Onetime capex	Equipment, integration, training	80,000
Simple undiscounted payback	80,000 / 26,475	3.02 years

Table 4. Illustrative sensitivity scenarios: fixed SAR 80,000 investment

Scenario	Gross benefit (SAR/y)	Recurring cost (SAR/y)	Net (SAR/y)	Payback (years)
Conservative	25,000	15,000	10,000	8.00
Base case	38,475	12,000	26,475	3.02
Favourable	55,000	11,000	44,000	1.82

9. Managerial and policy implications

For retail operators, the most important management decision is where to begin. A diagnostic audit should identify recurrent stock discrepancies, downtime, billing disputes, energyintensive assets and preventable customer friction. Investments should be sequenced according to both expected value and data readiness. Electronic delivery and inventory reconciliation may have a stronger immediate control case than machinelearning forecasting where reliable historical records do not yet exist. Conversely, a large station network with robust data may benefit from regional replenishment models before adding customerfacing novelty features. Assahla et al. (2021) and Marques et al. (2021) show distinct technical opportunities; the managerial question is whether each solves a documented, sufficiently costly problem.

Workforce preparation should not be treated as a postinstallation training event. Site managers need to understand exception thresholds, frontline staff must be able to report incorrect readings without penalty, and technicians should know when a sensor issue requires manual inspection. Responsibilities should be mapped before the procurement of software, including who can change alert limits and who signs off on unresolved variances. An apparently precise dashboard may reduce decision quality if it encourages staff to defer judgement to uncalibrated indicators. Verhoef et al. (2021) and Vial (2019) locate the value of digitalisation in changes to routines and value creation; those changes require managerial sponsorship as well as functioning devices.

At a policy level, the most useful contributions may be common data definitions, minimum interoperability requirements, verified metrology procedures and guidance on environmental monitoring rather than prescribing a single vendor platform. Multisite benchmarking would become more meaningful if networks measured downtime, reconciliation differences, vapourcontrol inspections and electricity intensity consistently. Any benchmarking regime should allow for station size, location, customer mix, climate and operating hours. Saudiwide assessment would also benefit from confidential access to anonymised, qualitycontrolled station performance data and an agreed protocol for evaluating new technologies. The intent is to enable credible comparison without disclosing commercially sensitive information or transferring inappropriate safety responsibilities to an automated system.

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Sustainability should remain a decision constraint alongside profitability, not merely a separate reporting category. For example, greater dispenser availability is desirable only if supported by proper maintenance and fuelhandling procedures. An automated pricing or loyalty service should not erode privacy protections, and electricity savings should not compromise lighting or occupational safety. Yusuf and Lytras (2023) highlight the strategic role of coordination in environmental transformation, while international work on vapour exposure demonstrates why safeguards require actual monitoring and maintenance rather than promotional claims (Zeng et al., 2022; Shinohara et al., 2025). This multiobjective treatment is essential in a sector handling hazardous substances in public spaces.

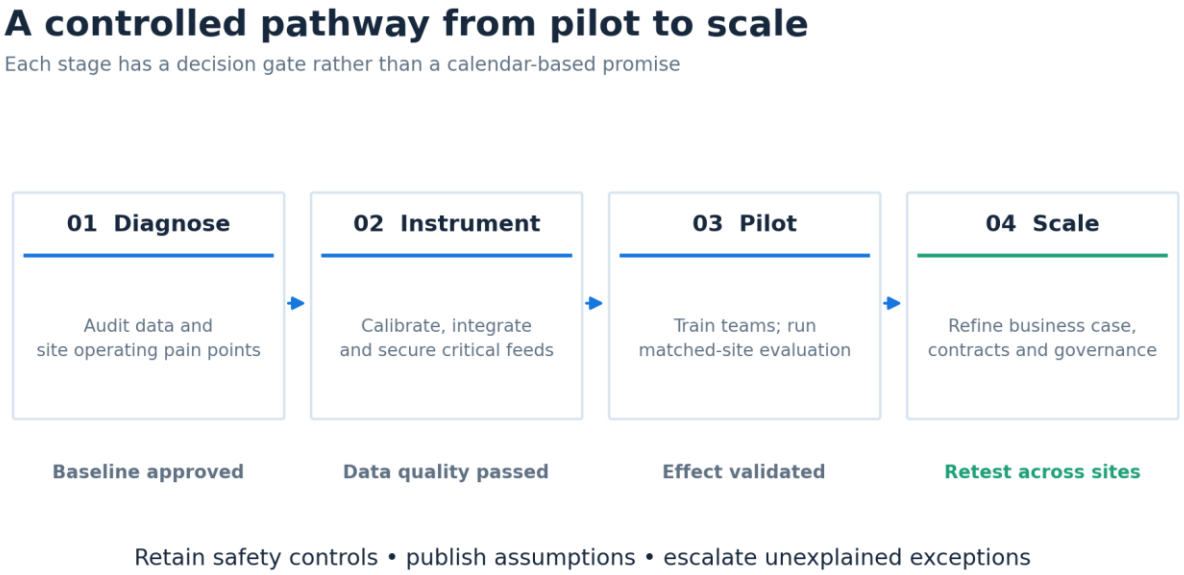


Figure 3. Phased implementation framework with evidencebased decision gates (authordeveloped synthesis).

10. Research limitations and agenda

The principal limitation is the scarcity of directly comparable, longitudinal evidence on digital transformation across Saudi petroleum retail sites. The national oil and gas studies included in this review examine broader corporate or sectoral issues, and international service station studies vary in sample size, technology maturity and regulatory setting. Many engineering papers describe functional prototypes rather than audited business cases; some optimisation studies evaluate mathematical scenarios rather than operational fleets. Consequently, the framework is a synthesis of plausible mechanisms supported by differentiated evidence, not a claim that the proposed package has been deployed and tested nationally. The financial numbers in Tables 2–4 are explicitly constructed assumptions and should not be cited as measured Saudi outcomes.

Future studies should distinguish at least four effects. The first is measurement improvement: more accurate or timely knowledge of equipment and stock. The second is behavioural improvement: quicker interventions, more consistent decisions and fewer unresolved exceptions. The third is economic improvement: lower avoidable cost or higher demonstrable contribution after implementation expenses. The fourth is sustainability improvement: verified reductions in site energy intensity, product loss or exposure under a documented environmental boundary. A longitudinal design could determine which of these effects appears first and whether early measurement improvements are necessary for subsequent economic gains. An additional research question concerns heterogeneity: do networkowned and independent sites, urban and intercity locations, or high and lowthroughput outlets require different investments?

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Cybersecurity and system reliability deserve independent investigation. Remote access creates both visibility and new attack surfaces; the coexistence of physical controls, payment information and enterprise data increases the consequences of inadequate segmentation. Researchers could conduct controlled failure simulations measuring recovery time, loss of data integrity and the effectiveness of manual fallback, with no interference to live safetycritical systems. The framework also raises an information governance question: who owns derived operational data when devices, cloud services and retail operators are supplied by separate firms? Clear contractual and technical standards may affect longterm economics more than additional predictive sophistication. These issues have counterparts in wider digitaltwin research but remain poorly established in retail deployment studies (Meza et al., 2024).

Finally, sustainability research should integrate fieldbased monitoring with appropriate control groups. For vapor control upgrades, measured concentrations should be considered alongside fuel handling volume, meteorology and maintenance records; for rooftop generation, avoided grid electricity should be reported separately from emissions associated with fuel sales; for replenishment, vehicle kilometers and stockout effects should be considered jointly. These designs would permit assessment of tradeoffs instead of a simplistic claim that every digital feature improves every sustainability indicator. An evidence agenda built around transparent baselines, replicable outcome definitions and negative as well as positive results would strengthen both journal scholarship and investment decisions.

11. Conclusion

Digital transformation can change petroleum retail performance when it connects reliable physical measurements to accountable operational decisions. The evidence assembled here identifies plausible applications in fuel reconciliation, pump availability, tanker replenishment, payment processing, convenience operations, energy management and vapourcontrol oversight. Nevertheless, it does not support a universal percentage productivity gain for Saudi Arabia. The proposed framework therefore places data validity, workflow ownership, safety and measurable counterfactuals between technological capability and claimed outcome. The illustrative calculations show how a station operator could evaluate options without misrepresenting hypothetical values as empirical results. For Saudi retail networks, the strongest route towards efficient and sustainable operations is a staged programme that begins with control integrity and workforce readiness, pilots a limited set of measurable interventions, validates their financial and environmental consequences, and scales only those practices whose effects persist across different site conditions.

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