

Integrated Granoformix Automation Improves Efficiency, Product Consistency, Hygiene, and Traceability in a Food Microenterprise

Rudi Nurdiansyah¹, Erwin Komara Mindarta², Eddy Rudiyanto³, Marji⁴, Andre Triansyahputra⁵, Aswangga Bhagas Ramadhan⁶, Eka Dyah Febriyanti⁷

^{1,2,3,4,5,6,7}Universitas Negeri Malang, Jl. Semarang No. 5, Sumbersari, Kec. Lowokwaru, Kota Malang, Jawa Timur 65145.

E-mail: erwin.komara.ft@um.ac.id

* Corresponding Author

 <https://doi.org/10.31004/jerkin.v5i1.7753>

ARTICLE INFO

Article history

Received: 2 September 2026

Revised: 7 September 2026

Accepted: 29 September 2026

Kata kunci:

UMKM pangan; otomasi skala tepat; manufaktur pangan cerdas; ketertelusuran digital; efisiensi produksi

Keywords

food MSME; appropriate-scale automation; smart food manufacturing; digital traceability; production efficiency



ABSTRACT

Penelitian ini mengevaluasi Granoformix, sistem pembentukan dan pengemasan granola bar, sebagai inti intervensi sosioteknis pada UMKM di Malang, Indonesia. Implementasi sebelum-sesudah menggabungkan proses berbasis PLC dengan aliran satu arah, GMP/SSOP, pelatihan operator, pencatatan terstandar, dasbor digital, dan ketertelusuran kode QR. Dimensi dan massa dinilai pada 100 batang sebelum dan sesudah implementasi. Waktu produksi per batch menurun dari 318 menjadi 205 menit (-35,5%), keluaran meningkat dari 320 menjadi 430 batang, dan produktivitas naik dari 60 menjadi 126 batang per jam. Kesesuaian dimensi meningkat dari 66% menjadi 95%, kesesuaian berat dari 68% menjadi 96%, dan produk cacat menurun dari 10,0% menjadi 3,3%. Skor audit higiene meningkat dari 58 menjadi 74, kelengkapan rekaman digital mencapai 96,1%, dan biaya produksi turun dari Rp5.500 menjadi Rp4.500 per batang. Otomasi skala tepat menghasilkan peningkatan mutu, higiene, ketertelusuran, dan biaya bersamaan ketika dipadukan dengan proses terstandar dan kompetensi tenaga kerja.

This study evaluated Granoformix, a granola-bar forming and packaging system, as the core of a socio-technical intervention in a microenterprise in Malang, Indonesia. A before-and-after implementation combined PLC-controlled processing with one-way flow, GMP/SSOP, operator training, standardized records, a digital dashboard, and QR-based traceability. Product dimensions and mass were assessed in 100 bars before and after implementation. Batch time decreased from 318 to 205 min (-35.5%), output increased from 320 to 430 bars, and productivity rose from 60 to 126 bars h⁻¹. Dimensional compliance increased from 66% to 95%, weight compliance from 68% to 96%, and defects decreased from 10.0% to 3.3%. Hygiene audit scores increased from 58 to 74, digital-record completeness reached 96.1%, and production cost declined from IDR 5,500 to IDR 4,500 per bar. Appropriate-scale automation delivered operational, quality, hygiene, traceability, and cost gains when embedded within standardized processes and workforce capability.



This is an open access article under the CC-BY-SA license.

How to Cite: Rudi Nurdiansyah et al (2026). Integrated Granoformix Automation Improves Efficiency, Product Consistency, Hygiene, and Traceability in a Food Microenterprise 5(1). <https://doi.org/10.31004/jerkin.v5i1.7753>

INTRODUCTION

Food micro, small, and medium enterprises (MSMEs) are central to local food economies because they convert agricultural and food ingredients into accessible products while providing employment and entrepreneurial opportunities. Their operating model, however, often combines small production volumes with limited capital, restricted floor area, modest technical staffing, and fragmented documentation. These constraints can slow the adoption of advanced manufacturing practices and make modernization qualitatively different from transformation in large factories. Reviews and empirical studies describe persistent financing, technology, and regulatory gaps in MSMEs, while research in food-processing SMEs emphasizes limited financial flexibility and the need for affordable, sustainable

modernization pathways (Martinravi & Krishnasamy, 2025; Raut et al., 2022). Readiness studies further show that many food-processing SMEs continue to operate with Industry 1.0-3.0 practices even while facing pressure to move toward more human-centered, resilient, and digitally enabled production (Madhavan et al., 2024). Accordingly, the challenge is not simply to introduce more technology, but to introduce technology at a scale and level of complexity that the enterprise can operate, maintain, and absorb.

Automation is attractive in this context because food production contains many repetitive handling, portioning, loading, forming, and packaging tasks in which process consistency and labor exposure are closely linked. Food-manufacturing research links automation and control with process repeatability, robotics, and intelligent production, yet adoption remains uneven (Dahm & Mathur, 1990; Khan et al., 2018; Raffik et al., 2023). Accorsi et al. (2019) identified low margins, the prevalence of SMEs, and the flexibility required for food handling as barriers to automation, while Taha (2026) reported that robotics can improve regularity and reduce human exposure but remains constrained by investment cost, operator skills, and SME readiness. These tensions are important because a technically sophisticated solution can fail if it is financially disproportionate, difficult to clean, or dependent on expertise unavailable at the point of use.

Evidence from small-scale food applications nevertheless indicates that targeted automation can yield substantial gains when it is matched to a specific bottleneck. In an Indonesian food SME producing wingko, integration of material handling and baking using a karakuri-based approach reduced cycle time by approximately 39% (Anggrahini et al., 2020). Robotic loading for home-meal-replacement production improved throughput in two operating scenarios and could be run by one worker (Baek et al., 2024), while an automated wrapper for roasted glutinous rice reduced wrapping time and improved consistency (Basar et al., 2025). These studies support targeted automation around specific SME bottlenecks.

This observation has motivated staged and retrofit-oriented models of digital manufacturing. Konur et al. (2023) showed that a traditional food manufacturer could adopt Industry 4.0 capabilities by adapting existing machinery rather than replacing it outright, while Wang et al. (2021) proposed an Industry 3.5 logic for organizations that are not ready for direct migration to Industry 4.0. Urban et al. (2020) likewise demonstrated that Industry 4.0 tools can shorten process stages in an SME serving food-processing technology markets. Maturity-model research in agri-food SMEs stresses that roadmaps developed for large organizations may not fit firms with limited financial and human resources (Arena et al., 2023), and models for food manufacturing under Industry 5.0 similarly emphasize the need for guidance tailored to the changing strategic environment of SMEs (Saptaningtyas & Rahayu, 2020). Together, this literature supports an "appropriate-scale" interpretation of modernization: technology should solve the most consequential process constraints while remaining compatible with current organizational capability.

A further development in the literature is the integration of automation with lean, data, and decision-support practices rather than treating machinery as an isolated intervention. Amirkhanova et al. (2026) integrated lean manufacturing, industrial IoT, simulation, optimization, and analytics in a medium-scale bakery and reported reductions in cycle time, inter-operational waiting, planning time, and energy use. In snack manufacturing, Valles et al. (2025) combined SMED, predictive maintenance, line balancing, IoT, and machine learning to address changeover, downtime, and imbalance. Komori-Zevallos et al. (2023) similarly proposed a Lean 4.0 model for food SMEs that linked productivity, inventory, waste, forecasting, and visual analytics. This systems perspective is consistent with evidence that eliminating non-value-added activity can be as consequential as increasing nominal machine speed (Laghouag et al., 2024). It also aligns with the broader role of intelligent sensors and operational data in supporting timely decisions rather than merely recording production after the event (Coito et al., 2021).

For SMEs, however, digital transformation depends on organizational capability as much as on the technology stack. Food-SME studies have identified technological infrastructure, operating standards, organizational readiness, knowledge acquisition, and digital culture as important enablers of transformation (Chandrayan et al., 2023; Jewapatarakul & Ueasangkomsate, 2024). Frau et al. (2022) conceptualized agri-food digitalization as a progression from data generation and acquisition through storage, analysis, and exploitation, highlighting that firms differ markedly in how maturely they handle data. Field-oriented work further argues that SMEs need an operational data foundation that remains

interpretable and manageable under constrained deployment conditions (Kang & Park, 2026). Dashboards, analytics, and digital platforms can support resource optimization, information flow, business performance, market access, and resilience in food contexts (Hassani et al., 2025; Abdul Wahab et al., 2024; Samara et al., 2026; Mashoko, 2025; Musa et al., 2023).

Equipment reliability and maintenance are inseparable from this transition. Maintenance capability is equally important because SMEs often lack dedicated technical staff. Low-cost retrofit monitoring, phased digital-twin strategies, predictive maintenance, and online quality sensing have therefore been proposed to improve reliability under constrained conditions (Kotsilitis et al., 2020a; Nasirinejad et al., 2026; Pech et al., 2021; Griffin et al., 2001). Maintainability, troubleshooting, and data visibility should therefore be designed alongside production equipment.

Food automation must also be evaluated against hygiene and quality, not only throughput. In small food-processing settings, inadequate GMP implementation and microbial contamination sources can persist when cleaning, facility practices, and worker behavior are insufficiently controlled (Malavi et al., 2018). Structured food-safety training can improve food-handler behavior, indicating that human capability remains a critical part of technical modernization (Malavi et al., 2021). At a more advanced level, Quality 4.0 approaches emphasize evidence-based, digitally supported quality systems, while research in microenterprises argues that technology should be integrated with management practices to support sustainable-development outcomes (Aviles-Sacoto et al., 2024). Automated inspection research in agri-food production similarly demonstrates how digital quality control can reinforce conformity verification and traceability (Sánchez-Rodríguez et al., 2025). The maturity of robotics itself is also influenced by organizational and implementation conditions rather than hardware capability alone (Aggogeri et al., 2024). Consequently, a food-MSME automation project should be judged by whether it simultaneously stabilizes product characteristics, reduces contamination opportunities, and creates routines that operators can sustain.

Traceability represents another layer of this integrated problem. Advanced supply-chain studies emphasize distributed ledgers, IoT monitoring, and governance mechanisms for secure provenance and verification, while also acknowledging adoption barriers and the need for human oversight in SMEs (Abaker, 2025). Reviews of blockchain-enabled food and agricultural traceability describe the value of linked identity and data across the supply chain, but they also point to implementation complexity (Ismail et al., 2023; Lv et al., 2023). For a microenterprise, the immediate value may therefore lie less in deploying the most advanced architecture and more in establishing reliable batch identity, structured records, rapid retrieval, and an accessible consumer-facing information layer. Technology-upgrading evaluations suggest that process and innovation assimilation should be assessed together with market and managerial outcomes (Rivera et al., 2020). Food-MSME digitalization likewise requires targeted financial, policy, and skill support while addressing adaptability, trust, and economic uncertainty (Ranjini et al., 2025; Yap & Al-Mutairi, 2024).

Despite these advances, the evidence base remains fragmented. Automation studies frequently report throughput or labor effects; digital-transformation studies emphasize data or organizational readiness; hygiene studies focus on behavior and compliance; and traceability studies often address supply-chain architectures rather than day-to-day microenterprise production. Less evidence is available on whether an appropriately scaled automation system can produce simultaneous gains in efficiency, product consistency, hygiene, documentation, traceability, unit cost, and market readiness when implemented as one socio-technical package. This gap is particularly relevant for micro food businesses, where process, people, information, and market presentation are tightly coupled and where isolated improvements can be undermined by bottlenecks elsewhere in the system.

Pickmeal Granola Bar, a food microenterprise in Bandungregosari, Sukun District, Malang, Indonesia, provided a field setting for evaluating this integrated proposition. Before intervention, production was semi-manual and sequentially fragmented. A 10-kg batch required 318 min and produced approximately 320 bars; only 66% of sampled bars met the complete dimensional specification, 68% met the 30 +/- 1.5 g weight specification, and about 10% were classified as defective. The baseline hygiene audit score was 58/100, multiple cross-flows occurred in the approximately 24 m² production room, and production records did not systematically connect batch identity, process parameters, quality results, sanitation, maintenance, and product disposition.

To address these interdependent constraints, Granoformix was developed as an Integrated Granola Bar Forming & Packaging Assembly combining PLC-controlled mixing and heating, press forming, enclosed cooling, automatic cutting, conveyor transfer, and heat sealing. The equipment was introduced together with a one-way production layout, GMP/SSOP, operator and maintenance training, standardized records, a Digital Production Dashboard, improved packaging, batch coding, and QR-based traceability. The study therefore evaluated whether this integrated intervention improved production efficiency and capacity, product consistency, defects and rework, hygiene and handling control, operator capability, documentation, digital traceability, consumer acceptance, and market-related performance. The central hypothesis was that appropriate-scale automation, when embedded within process standardization, workforce capability, hygiene management, and digital data practices, would increase efficiency without a quality or food-safety trade-off and would instead produce concurrent gains across operational, quality, hygiene, traceability, and market dimensions.

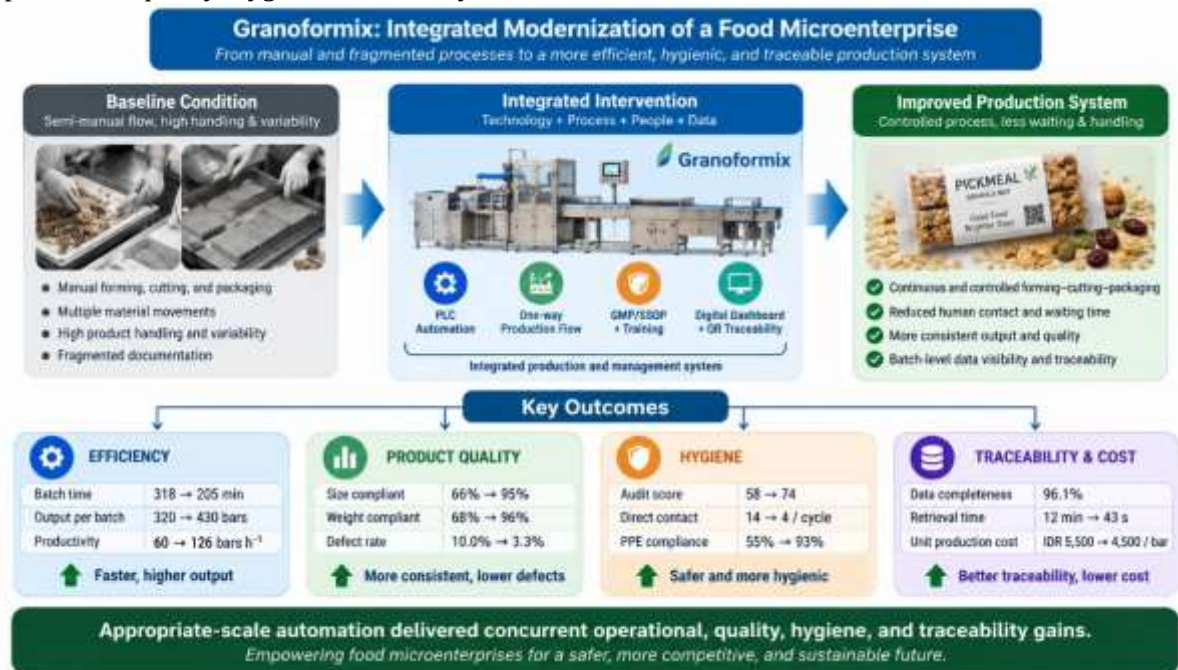


Figure 1. Integrated socio-technical architecture of the Granoformix intervention.

METHOD

Study design and setting

A before-and-after field implementation study was conducted at Pickmeal Granola Bar in Bandongrejosari, Sukun District, Malang, East Java, Indonesia. The unit of intervention was the production system rather than an individual machine component. Baseline measurements characterized the existing semi-manual process, after which the Granoformix line, revised production layout, hygiene procedures, training program, documentation system, and digital dashboard were introduced. Post-implementation performance was assessed during commissioning, functional trials, and routine production monitoring, including a four-week period of dashboard use and operational accompaniment.

The baseline production sequence comprised raw-material preparation, mixing and heating, cooling, manual forming, manual cutting, individual weighing, insertion into packaging, and manual sealing. Equipment was distributed across an approximately 24 m² room without a strict one-way flow. A standard batch used 10 kg of ingredients and produced approximately 320 bars. Following intervention, production continued to use 10 kg as the reference batch size, allowing direct comparison of time, output, and product quality at equivalent nominal input.

Granoformix technology

Granoformix was designed as a compact integrated line suitable for the spatial and infrastructure limitations of the partner enterprise. The assembled system measured approximately 4,200 x 1,250 x 1,750 mm and occupied about 8.4 m² of the production room while maintaining access for cleaning and

maintenance. The nominal working capacity was 10 kg of mixture per cycle. Electrical demand was approximately 3,850 W using a 220-V single-phase supply.

The upstream module comprised a 12-kg hopper, a SUS 304 stainless-steel heated mixing tank with a 10-kg working capacity, a 750-W mixing motor, and temperature and mixing-speed control. The standard operating set points established during commissioning were 62 degrees C for mixing/heating and 42 rpm for agitation. Product was then transferred to an automatic press-forming unit designed to produce a nominal 15-mm sheet thickness. A forming conveyor moved the sheet through an enclosed cooling chamber maintained at approximately 18-22 degrees C before cutting. The PLC-controlled cutting unit targeted bars of 90 x 35 mm, while the packaging section used a 160-mm food-grade film roll and heat sealing at approximately 155 degrees C for 1.2 s. A 7-inch human-machine interface provided access to production parameters, including temperature, conveyor speed, forming thickness, and sealing conditions. The standard conveyor speed was 1.8 m min⁻¹.

The machine was installed after the room layout was reorganized into sequential raw-material/preparation, processing, and clean/packaging zones. Mechanical and electrical installation was followed by calibration of temperature, conveyor speed, forming thickness, cutting dimensions, and sealing performance. Integrated functional testing consisted of five 10-kg cycles (50 kg total) during commissioning. Early issues, including dough accumulation at the forming unit, irregular product spacing, and cutting-sensor delay, were corrected through guides, conveyor-speed adjustment, and sensor repositioning. After these corrections, the system operated for approximately 205 min per production cycle without mechanically or electrically induced interruption during the reported integrated trials.

Integrated process, hygiene, and capability intervention

The physical equipment was implemented together with process-management changes. A one-way flow was established to minimize cross-movement between raw materials, work-in-process, workers, and finished goods. Production space was divided into a raw-material/preparation zone (approximately 6.5 m²), a processing zone (10.5 m²), and a clean/packaging zone (7 m²). Equipment transfer between zones was restricted unless cleaning and sanitation had been completed.

Eight hygiene-oriented procedures were established for raw-material receipt, personal hygiene, equipment cleaning, room sanitation, Granofomix operation, product handling, waste management, and corrective action. Cleaning was structured into pre-production, between-batch, post-production, and weekly deep-cleaning activities. Food-contact surfaces were cleaned using a sequence of residue removal, food-grade detergent washing, rinsing, sanitation, and drying. Personal protective requirements included head covering, mask, apron, food-grade gloves, and dedicated footwear.

Five participants (one owner and four production workers) completed 12 h of training over two days. Training covered machine components, start-up and shutdown, HMI settings, emergency stopping, GMP/SSOP, cleaning, preventive maintenance, and troubleshooting. Six basic malfunction scenarios were used for troubleshooting practice. Standardized checklists were introduced for pre-operation and post-operation inspection, preventive maintenance, hygiene, and corrective action.

Digital production management and traceability

A web-responsive Digital Production Dashboard was introduced to integrate raw-material inventory, batch production, product quality, maintenance, cost, finished-goods inventory, and sales. User access was separated among administrator, production operator, and quality-control roles. During four weeks of monitoring, the dashboard captured 40 production batches over 20 working days. Each batch record could include date, operator, start and finish times, Granofomix parameters, output, quality results, defect information, and raw-material use.

Traceability was extended from the dashboard to the package by assigning batch codes and adding QR codes. The QR-linked page provided product information and access to business communication and ordering channels. Traceability testing selected 20 packaged samples across 10 batches and measured the time required to retrieve associated production information. Packaging was simultaneously upgraded to a PET/PP food-grade laminate sized to the standardized bar, with batch identity, product information, and space for nutrition information.

Outcome measures

Operational efficiency was evaluated using total batch time, stage-specific processing time, inter-process waiting time, output per batch, output per hour, daily and monthly capacity, labor involvement,

manual transfer events, and reported worker fatigue. Stage times were recorded for mixing/heating, forming, cooling, cutting, and packaging. Labor involvement was expressed as person-hours per batch.

Product quality was assessed using dimensional and mass measurements. Samples of 100 bars were measured before and after implementation. The target dimensions were 90 $\pm$ 2 mm length, 35 $\pm$ 2 mm width, and 15 $\pm$ 1 mm thickness. Target mass was 30 $\pm$ 1.5 g. Reported means, ranges, standard deviations, compliance proportions, and defect classifications were extracted from the study dataset. Defects included irregular form, cracking/breakage, dimensions outside specification, mass outside tolerance, sealing failure, and packaging damage.

Hygiene was evaluated with a 25-indicator audit grouped into room cleanliness, equipment cleanliness, worker hygiene, process sanitation, and hygiene documentation. The overall score was reported on a 0-100 scale. Additional process indicators included cross-flow events, direct hand-product contact events, personal protective equipment compliance, handwashing compliance, residual material findings, and nonconformities at identified contamination-risk points.

Operator capability was evaluated by pre- and post-training knowledge scores and practical skill rubrics for operation, maintenance, safety, and GMP/SSOP. Documentation performance was measured through completeness and consistency of batch records, sanitation checklists, maintenance records, product-quality forms, defect records, and raw-material logs.

Packaging performance was assessed using sealing strength, leakage, cutting alignment, label position, QR readability, and 30-day physical-protection observations. Consumer acceptance was evaluated among 120 respondents (60 existing consumers and 60 prospective consumers in Malang) on a five-point scale covering package attractiveness, information clarity, perceived hygiene, perceived quality, ease of opening, trust, purchase intention, willingness to recommend, price appropriateness, and perceived readiness for modern retail. Business outcomes included unit production cost, monthly sales volume, monthly revenue, and time to fulfill a 2,500-bar order.

Statistical analysis

The analysis prioritized the observed dataset and did not generate synthetic individual-level values. Continuous product measurements with reported sample size, mean, and standard deviation ($n=100$ bars in each condition) were compared using Welch's two-sample t test, which does not assume equal variances. Mean differences are reported as after-minus-before values with approximate 95% confidence intervals. Hedges' g was calculated as a standardized effect-size estimate. For clearly enumerated compliance outcomes, two-proportion z tests were used to compare the proportion of bars meeting complete dimensional and weight specifications. Packaging leakage was compared using the same approach because the report specified equal 200-package samples before and after implementation. Relative risks and absolute percentage-point differences are reported.

For outcomes lacking replicate-level variance, pairing information, or individual observations - including process time, hygiene audit score, labor-hours, dashboard completeness, consumer mean scores, and business performance - analysis was descriptive. Relative change was calculated as $(\text{post} - \text{baseline})/\text{baseline} \times 100\%$ where meaningful. Percentage-point change was used for proportions when it provided clearer interpretation. Because this was a single-site before-and-after field implementation without a parallel control group, inferential statistics are interpreted as supporting evidence for measured product-level changes rather than as proof of causal effects for all system-level outcomes.

RESULTS AND DISCUSSION

System deployment and functional performance

Granoformix was successfully installed within the existing 24 m² production facility without requiring a new production room. Reorganization into one-way movement reduced the number of cross-flow events between materials, work-in-process, workers, and packaged product from six to one per production cycle. Calibration showed close agreement between programmed and observed operating conditions: the mixing-tank temperature differed from the reference by an average of 0.8 degrees C, the 1.8 m min⁻¹ conveyor setting produced an average observed speed of 1.78 m min⁻¹, and the forming unit produced an average thickness of 15.1 mm. Initial sealing tests produced 97 successfully sealed packages per 100, increasing to 99% after roll alignment and sealing-pressure adjustment.

Five integrated commissioning cycles using 50 kg of raw material confirmed that the line could run continuously after early mechanical and sensor adjustments. The average reported output was 430

bars per cycle, and the overall success rate for products formed, cut, and sealed to standard was 96.7%. Component operation success was reported at 98.4%. These functional results established a sufficiently stable platform for routine production and for the broader process-management intervention shown in Figure 1.

Production efficiency and capacity

Total processing time for the reference 10-kg batch decreased from 318 min to 205 min, a reduction of 113 min or 35.5%. All major processing stages became shorter (Figure 2). Mixing and heating decreased from 52 to 38 min (-26.9%), forming from 74 to 32 min (-56.8%), cooling from 48 to 30 min (-37.5%), cutting from 61 to 42 min (-31.1%), and packaging from 83 to 63 min (-24.1%). The largest absolute and relative improvement occurred in forming, which had previously depended heavily on manual spreading and shaping.

The time reduction was not explained only by faster local operations. Inter-process waiting time decreased from 67 to 18 min per cycle (-73.1%) after forming, cooling, cutting, and packaging were connected through a more continuous material flow. Reported cycle-to-cycle variation in total production time also narrowed from approximately +/-21 min to +/-7 min. This suggests that integration reduced both the average duration and the unpredictability of production.

Output increased from 320 to 430 bars per batch (+34.4%). When combined with the shorter cycle, nominal productivity increased from approximately 60 to 126 bars h⁻¹ (+110%). The enterprise continued to operate two cycles per day so that preparation, cleaning, quality inspection, and administrative tasks could be maintained; nevertheless, daily capacity increased from 640 to 860 bars and projected 24-day monthly capacity from 15,360 to 20,640 bars. At the 30-g target mass, this corresponded to an increase in potential finished-product output from about 460.8 to 619.2 kg month⁻¹.

The integrated line also reduced manual workload. Production previously required four workers rotating through mixing, forming, cutting, weighing, and packaging. Routine operation after implementation could be handled by three active production roles: primary operator, quality supervisor, and material/finished-product support. Labor involvement decreased from 21.2 to 10.3 person-hours per batch (-51.4%). Direct hand-product contacts between forming and packaging declined from 14 to four events per cycle (-71.4%), and manual transfers between process stations declined from six to one. Worker fatigue scores on the reported 1-5 scale decreased from 4.3 to 2.4 (-44.2%). These changes indicate that automation shifted work from repetitive physical manipulation toward monitoring, sanitation, quality control, and documentation.

Table 1 summarizes the major operational, quality, hygiene, digital, and market indicators. The combined pattern is important: higher throughput occurred concurrently with lower variation, fewer defects, lower unit cost, and improved hygiene rather than at their expense.

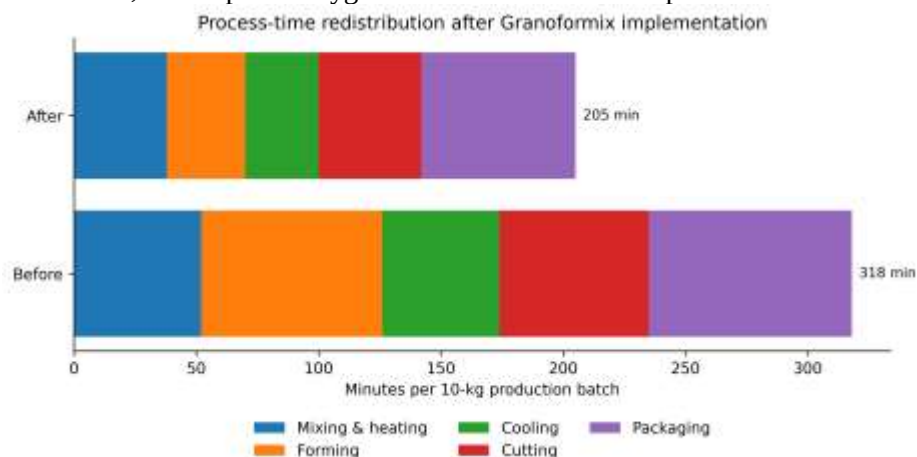


Figure 2. Production-time composition for a 10-kg batch before and after Granoformix implementation. Total batch time decreased from 318 to 205 min; forming showed the largest relative reduction.

Table 1. Key before-and-after indicators of the integrated Granoformix intervention (pp = percentage points; PPE = personal protective equipment)

Integrated Graniformix Automation Improves Efficiency, Product Consistency, Hygiene, and Traceability in a Food Microenterprise, Rudi Nurdiansyah, Erwin Komara Mindarta, Eddy Rudyanto, Marji, Andre Triansyahputra, Aswangga Bhagas Ramadhan, Eka Dyah Febriyanti

4229

Domain	Indicator	Baseline	Post-intervention	Change
Efficiency	Batch time	318 min	205 min	-35.5%
Efficiency	Output per batch	320 bars	430 bars	+34.4%
Efficiency	Productivity	60 bars h-1	126 bars h-1	+110%
Labor	Labor involvement	21.2 person-h	10.3 person-h	-51.4%
Handling	Direct product contacts	14/cycle	4/cycle	-71.4%
Quality	Dimension compliant	66%	95%	+29 pp
Quality	Weight compliant	68%	96%	+28 pp
Quality	Defect rate	10.0%	3.3%	-6.7 pp
Hygiene	Audit score	58/100	74/100	+27.6%
Hygiene	PPE compliance	55%	93%	+38 pp
Digital	Data completeness	Not available	96.1%	Implemented
Cost	Production cost/bar	IDR 5,500	IDR 4,500	-18.2%
Market	Consumer acceptance	3.22/5	4.49/5	+39.4%
Market	Monthly sales	12,600 bars	16,200 bars	+28.6%
Market	Monthly revenue	IDR 100.8 M	IDR 129.6 M	+28.6%

Product consistency and defects

Product geometry became substantially more consistent after the forming and cutting operations were placed under controlled mechanical settings. Before implementation, mean length was 87.6 mm (SD 3.4), width 36.8 mm (SD 2.3), and thickness 14.4 mm (SD 1.9). After implementation, the corresponding values were 90.2 mm (SD 0.9), 35.1 mm (SD 0.8), and 15.1 mm (SD 0.5), all close to the target geometry of 90 x 35 x 15 mm. Welch tests based on the reported 100-bar samples indicated clear shifts in the mean dimensions toward the intended set points (Table 2). Standardized mean shifts were large for length and width and moderate for thickness.

More important operationally, dispersion narrowed. The coefficient of variation for length decreased from approximately 3.9% to 1.0%, for width from 6.3% to 2.3%, and for thickness from 13.2% to 3.3%. The percentage of bars meeting all dimensional requirements simultaneously increased from 66% to 95%, an absolute increase of 29 percentage points (95% CI 18.8 to 39.2; $p < 0.001$ under an independent-proportion approximation). Figure 3 shows the change in dimensional compliance, weight compliance, and defect rate.

Mass control showed a similar pattern. Mean bar mass moved from 30.9 g (SD 2.1) to 30.1 g (SD 0.7), much closer to the 30-g nominal target and with a two-thirds reduction in standard deviation. The proportion within the 28.5-31.5 g tolerance increased from 68% to 96%, a 28-percentage-point increase (95% CI 18.1 to 37.9; $p < 0.001$). The reduction in variation also had a material-efficiency implication. The report estimated that uncontrolled overfill decreased from an average of about 0.9 g per bar to 0.1 g per bar, equivalent to a reduction of approximately 490 g day⁻¹ or 11.76 kg month⁻¹ at the stated production schedule.

Average defect rate declined from 10.0% (approximately 32 of 320 bars per cycle) to 3.3% (approximately 14 of 430). Rework declined from 5.9% to 1.6%, while products that could not be marketed as primary product declined from 4.1% to 1.6%. Rework time decreased from 24 to 8 min per batch. The defect reduction was distributed across irregular shape, cracking or breakage, off-size product, off-weight product, and packaging damage. Sealing defects remained relatively uncommon, and routine sealing success after implementation reached approximately 99.3%.

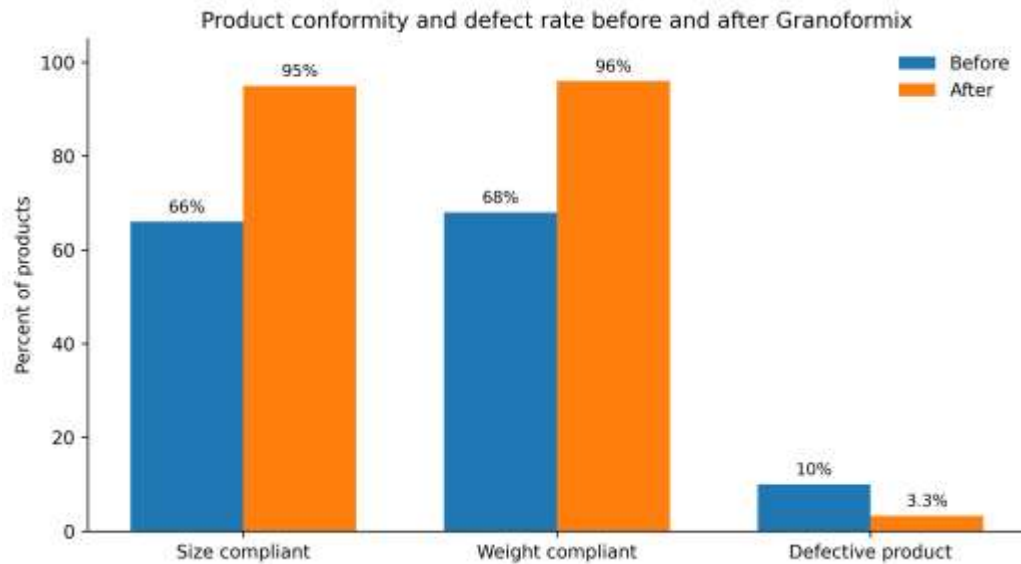


Figure 3. Product conformity and defect rate before and after Granofomix. Size and weight compliance increased substantially while the reported overall defect rate decreased.

Table 2. Exploratory inferential comparisons for outcomes with adequate reported sample and dispersion/count information

Endpoint	Baseline	Post	Difference (95% CI)	Effect	p
Length (mm)	87.6 (3.4)	90.2 (0.9)	+2.60 [+1.90, +3.30]	$g=+1.04$	<0.001
Width (mm)	36.8 (2.3)	35.1 (0.8)	-1.70 [-2.18, -1.22]	$g=-0.98$	<0.001
Thickness (mm)	14.4 (1.9)	15.1 (0.5)	+0.70 [+0.31, +1.09]	$g=+0.50$	<0.001
Weight (g)	30.9 (2.1)	30.1 (0.7)	-0.80 [-1.24, -0.36]	$g=-0.51$	<0.001
Size compliance	66/100 (66.0%)	95/100 (95.0%)	+29.0 pp [+18.8, +39.2]	RR=1.44	<0.001
Weight compliance	68/100 (68.0%)	96/100 (96.0%)	+28.0 pp [+18.1, +37.9]	RR=1.41	<0.001
Package leakage	10/200 (5.0%)	2/200 (1.0%)	-4.0 pp [-7.3, -0.7]	RR=0.20	0.019

Note. Continuous measures are mean (SD), n=100 bars per condition, analyzed using Welch's t test; effect is Hedges' g. Proportions were compared using a two-proportion z approximation; effect is relative risk (RR). Differences are post minus baseline. For dimensions and weight, the direction of the mean shift should be interpreted relative to the target specification (90 x 35 x 15 mm; 30 g). No synthetic raw observations were generated.

Hygiene, sanitation, and operator capability

The hygiene audit score increased from 58/100 to 74/100, a 16-point or 27.6% relative increase. Improvement was observed across all five audit domains: room cleanliness increased from 60 to 76; equipment cleanliness from 62 to 80; worker hygiene from 56 to 72; process sanitation from 58 to 74; and hygiene documentation from 54 to 68. The number of audit indicators judged to meet the required standard increased from 14 of 25 to 21 of 25. Major nonconformities decreased from seven to two and minor nonconformities from 11 to five.

Behavioral and process observations supported the audit trend. Personal protective equipment compliance increased from 55% to 93%, and handwashing compliance from 60% to 95%. Residual material findings on equipment decreased from an average of five to one per cycle. Nonconformities at five identified contamination-risk points decreased from 18 to five over the evaluation period.

Equipment-cleaning time decreased from 46 to 34 min as the sequence and division of responsibilities became standardized.

Operator training produced gains in both knowledge and practical skill. Mean knowledge score increased from 54.8 to 87.6. Practical operating skill increased from 48 to 88, maintenance competence from 42 to 84, and GMP/SSOP competence from 58 to 90. All five participants met the stated threshold for basic operation, safety, and hygiene competence, while four of five were able to perform preventive maintenance independently. Average troubleshooting time for light faults decreased from 26 to 11 min, and six of seven reported light faults during accompaniment were resolved by operators using the standardized procedure without direct intervention from the project team.

Documentation, digital management, and traceability

Ten core operational documents were introduced, covering Granoformix operation, cleaning and sanitation, preventive maintenance, troubleshooting, hygiene monitoring, batch production, quality inspection, defects, raw-material use, and maintenance history. Average consistency of use during accompaniment was 95.6%. Batch records were complete for 38 of 40 production batches, quality-inspection forms for 39 of 40, hygiene checklists for 19 of 20 observed production days, and raw-material records for 39 of 40 batches.

The Digital Production Dashboard was used for four consecutive weeks. Across 20 production days there were 96 access sessions, averaging 4.8 sessions per day. All 40 batches were registered and overall digital data completeness reached 96.1%. The agreement between physical inventory and digital stock records increased from 76% to 96%. Weekly reporting time decreased from 145 to 38 min (-73.8%), and the report documented 12 operational decisions supported by dashboard information, including raw-material purchasing, conveyor-speed adjustment, and packaging-roll procurement.

Batch identification linked the physical product to production information. Traceability testing of 20 samples from 10 batches showed that product information could be retrieved in an average of 43 s, compared with approximately 12 min before the structured system, a reduction of about 94%. QR codes were readable in all 200 packages tested for scanning performance. During the four-week period, the QR-linked page recorded 1,248 scans, including 318 visits to the catalog/order channel and 188 visits to social media; 76 transactions were associated with catalog visits originating from QR access.

Packaging, consumer acceptance, and business outcomes

Packaging quality improved on visual, functional, and information-related measures. The visual-quality score increased from 3.08 to 4.56 on a five-point scale. Correct label positioning increased from 64% to 96%, completeness of product information from 45% to 95%, and unused space inside the package decreased from 38% to 17%. In the 200-package integrity test after implementation, mean seal strength was 22.6 N against an 18-N minimum criterion, 198 packages (99%) showed no leakage, 194 (97%) met cutting-alignment criteria, 192 (96%) met label-position criteria, and all 200 QR codes were readable. The baseline leakage rate was reported as 5% in an equal-sized sample, compared with 1% after implementation; the absolute reduction was 4.0 percentage points (95% CI 0.7 to 7.3 percentage points; $p=0.019$).

Consumer evaluation among 120 respondents improved across all ten assessed dimensions (Figure 4). Mean overall acceptance increased from 3.22 to 4.49 (+39.4%). Perceived hygiene increased from 3.18 to 4.63, perceived quality from 3.31 to 4.57, information clarity from 2.94 to 4.52, package attractiveness from 3.08 to 4.56, and perceived modern-retail readiness from 3.35 to 4.62. Purchase intention increased from 3.24 to 4.47, and willingness to recommend from 3.20 to 4.45. Because individual paired consumer ratings and dispersion were not available in the source dataset, these changes were treated descriptively rather than subjected to significance testing.

Commercial indicators changed in the same favorable direction. Unit production cost decreased from approximately IDR 5,500 to IDR 4,500 per bar (-18.2%), even though total batch cost increased from approximately IDR 1,760,000 to IDR 1,935,000 because more products were produced. A 2,500-bar order that previously required approximately four working days could be completed in about three days. Monthly sales volume increased from 12,600 to 16,200 bars (+28.6%), and monthly revenue over the reported comparison period increased from approximately IDR 100.8 million to IDR 129.6 million (+28.6%). During the monitored period, 16,200 of 16,925 marketable bars were sold, corresponding to 95.7% of products classified as marketable.

Taken together, the results show a coherent chain of improvement: integration reduced time and handling; controlled forming and cutting reduced variation; reduced handling plus standardized hygiene improved process control; batch documentation and digital records increased observability; and improved consistency, packaging, information, and cost position were accompanied by stronger consumer ratings and sales performance.

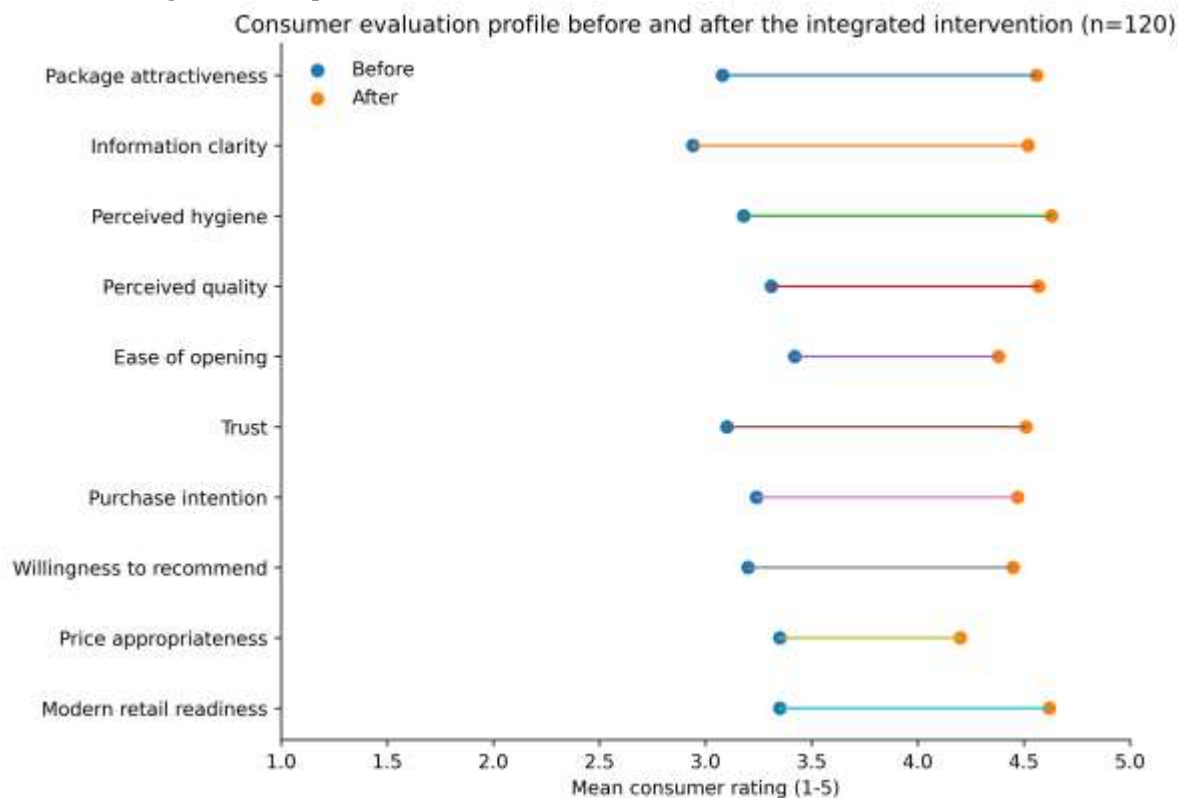


Figure 4. Consumer evaluation profile before and after the integrated intervention (n=120). All ten mean ratings increased on the reported five-point scale; inferential testing was not performed because individual-level paired data and dispersion were unavailable.

Principal findings

The Granoformix intervention produced a consistent pattern of improvement across production, product conformity, hygiene, documentation, and market-facing outcomes. For the same nominal 10-kg batch, cycle time decreased by 35.5%, output increased by 34.4%, and calculated hourly productivity more than doubled. These operational gains were accompanied by a 51.4% reduction in labor-hours per batch and a 73.1% reduction in inter-process waiting time. Crucially, higher throughput did not coincide with deteriorating quality. Dimensional compliance increased from 66% to 95%, weight compliance from 68% to 96%, and the reported defect rate declined from 10.0% to 3.3%. The hygiene audit score increased by 27.6%, digital-record completeness reached 96.1%, and unit production cost decreased by 18.2%. The pattern therefore supports the study's central proposition: in this field setting, productivity, consistency, hygiene, traceability, and cost performance improved concurrently when automation was implemented as part of an integrated production system rather than as a stand-alone machine.

The time reduction is comparable in direction with other targeted food-production interventions, although study designs differ. Cycle-time, waiting-time, throughput, and wrapping-time gains have been reported in food SMEs and related production settings using integrated handling, digitalized bakery systems, robotic loading, and automated wrapping (Anggrahini et al., 2020; Amirkhanova et al., 2026; Baek et al., 2024; Basar et al., 2025). Granoformix extends this evidence by linking operational improvement with measured changes in product conformity, hygiene, traceability, and market-related indicators.

Why integration mattered more than isolated automation

The strongest mechanism in the present dataset is the reduction of fragmentation between operations. Forming delivered the largest stage-specific time saving, but total cycle improvement also

reflected a 49-min reduction in inter-process waiting and a decrease in manual transfer from six events to one. Thus, the intervention did not simply make individual tasks faster; it changed the flow relationship among forming, cooling, cutting, and packaging. This interpretation is consistent with lean-oriented evidence that reducing non-value-added motion, waiting, and imbalance can be as important as increasing nominal machine speed (Laghouag et al., 2024; Valles et al., 2025). Komori-Zevallos et al. (2023) likewise framed food-SME productivity improvement as the outcome of combining lean practices, intelligent systems, forecasting, and decision support rather than relying on a single technology.

This systems interpretation also helps explain the labor findings. Person-hours per batch fell by approximately half, but the intervention did not eliminate the human role. Work shifted from repeated spreading, cutting, weighing, transfer, and sealing toward supervision, sanitation, quality inspection, documentation, and maintenance. Such reallocation is compatible with the logic of collaborative and human-centered automation, in which technical efficiency is combined with human flexibility and operational oversight (Accorsi et al., 2019; Taha, 2026). It also resembles staged modernization approaches proposed for SMEs that cannot move directly to highly autonomous Industry 4.0 systems (Wang et al., 2021; Madhavan et al., 2024). The implication is that appropriate-scale automation should be evaluated by the quality of the new human-machine work system, not merely by the number of manual tasks removed.

Technology-context fit was equally important. Granoformix was sized around the 10-kg batch, available floor area, single-phase electricity, workforce, and maintenance capacity. Agri-food maturity research cautions that large-firm roadmaps may not translate directly to SMEs (Arena et al., 2023), while Konur et al. (2023) showed that Industry 4.0 capability can be built without wholesale replacement of legacy assets. Here, control complexity was similarly bounded by the microenterprise's operational reality.

Process control, product consistency, and hygiene

The reduction in dimensional and weight variation provides the clearest product-level evidence that the intervention changed process capability. Standard deviations for length, width, thickness, and mass decreased markedly, and mean values moved closer to target specifications. These outcomes are consistent with the foundational role of automated control and sensing in maintaining process set points (Dahm & Mathur, 1990) and with more recent quality-management approaches that emphasize timely, evidence-based conformity assessment (Sánchez-Rodríguez et al., 2025). In practical terms, stable geometry affects more than appearance: it supports predictable cooling, package fit, portioning, net-weight control, raw-material yield, and repeatable presentation. The decline in overfill reported in the dataset also illustrates how product consistency can translate into material efficiency.

The hygiene improvement must be interpreted as a joint effect of technology, layout, procedures, and behavior. Direct hand-product contact decreased by 71.4%, but the audit also improved because one-way zoning, personal protective equipment, handwashing, cleaning schedules, documented sanitation, and corrective-action routines were introduced concurrently. This distinction matters because automated equipment does not itself guarantee food safety. Malavi et al. (2018) identified GMP and contamination weaknesses in small-scale food processing, and Malavi et al. (2021) showed that structured food-safety training can improve handler behavior. The Granoformix findings reinforce this socio-technical view: enclosed transfer and reduced handling lowered exposure opportunities, while GMP/SSOP and training created the behavioral controls needed to sustain the benefit.

At the same time, the final hygiene score of 74/100 should not be interpreted as complete safety validation. The source dataset identified remaining needs for periodic microbiological testing, water-quality monitoring, and stronger documentation discipline. The intervention therefore created a more controlled and auditable process, but not a substitute for microbiological verification, regulatory compliance, or formal shelf-life validation. This distinction is consistent with Quality 4.0 arguments that digital and automated tools should reinforce, rather than replace, quality-management systems (Aviles-Sacoto et al., 2024). It also reflects the broader observation that robotics maturity depends on organizational capability and implementation practices, not hardware alone (Aggogeri et al., 2024).

Digital traceability as an operational capability

The digital layer changed production records from a fragmented administrative activity into a usable management resource. During four weeks, all 40 production batches were registered, overall data

completeness reached 96.1%, and agreement between physical inventory and digital records increased to 96%. Weekly reporting time fell from 145 to 38 min, and the dataset documented 12 operational decisions supported by dashboard information. This progression closely matches the data-handling framework described by Frau et al. (2022), in which value emerges when firms move beyond data generation and storage toward analysis and exploitation. It also supports Kang and Park's (2026) argument that constrained SMEs first need a dependable operational data foundation before advanced analytics can provide sustained value.

The dashboard was deliberately simpler than many Industry 4.0 architectures. This matched evidence that food-SME transformation depends on infrastructure, standards, knowledge, and organizational readiness, and that phased digital adoption can reduce implementation risk (Chandrayan et al., 2023; Jewapatarakul & Ueasangkomsate, 2024; Nasirinejad et al., 2026). Linking batch identity, process parameters, inspection, materials, and maintenance created actionable visibility without requiring a complex enterprise platform.

Traceability followed the same principle. Advanced frameworks using blockchain and IoT can improve provenance, transparency, and verification, but they also introduce governance and adoption challenges for SMEs (Abaker, 2025; Ismail et al., 2023; Lv et al., 2023). In the present system, consistent batch codes, digital records, and QR-linked information reduced product-information retrieval time from approximately 12 min to 43 s. This does not replicate blockchain-level distributed traceability, but it establishes the more fundamental capability of linking a physical product to its production history. The QR layer also created a consumer interface, illustrating how a traceability identifier can serve operational transparency and market communication simultaneously.

From operational improvement to market readiness

Internal process changes were reflected in consumer-facing outcomes. Overall consumer acceptance increased from 3.22 to 4.49, while perceived hygiene, perceived quality, information clarity, and modern-retail readiness all improved. These results are directionally consistent with the broader literature showing that digital transformation can strengthen food-SME performance and decision-making when it is aligned with the business environment and organizational capability (Abdul Wahab et al., 2024; Samara et al., 2026). Frugal digital technologies have also been associated with better information transfer and market reach in food SMEs (Mashoko, 2025), while digital platforms have supported continuity and market access in local agri-food systems (Musa et al., 2023).

The commercial indicators also moved favorably: cost per bar decreased, the time needed to fulfill a 2,500-bar order shortened, monthly sales increased, and reported monthly revenue rose by 28.6% over the comparison period. These changes should not be interpreted as causal estimates because the design lacked a concurrent control and could not isolate seasonality, promotion, demand shifts, or other business changes. Nevertheless, the operational pathway is plausible: higher capacity, lower defects, lower unit cost, more consistent packaging, and more complete product information collectively increase the enterprise's ability to supply and present a standardized product. Technology-upgrading studies similarly emphasize that process and innovation assimilation should be linked with market and managerial outcomes when evaluating MSME interventions (Rivera et al., 2020).

Implications for food MSMEs and technology-transfer programs

The practical implication is that food-MSME automation should be designed as a socio-technical package: hardware, process redesign, operator capability, hygiene, maintenance, and proportionate data systems. Predictive-maintenance research supports low-cost staged monitoring (Kotsilitis et al., 2020a; Pech et al., 2021), while food-MSME digitalization requires support for finance, policy, and skills (Ranjini et al., 2025). Operator training should therefore cover troubleshooting and cleaning as seriously as normal production.

The findings also argue for a broader evaluation framework. Throughput alone would have captured only one portion of the intervention's value. Technology-transfer programs should assess product variability, sanitation, worker burden, documentation, traceability, cost, and adoption alongside capacity. This is consistent with evidence that digital transformation and technology maturity in SMEs are conditioned by human and organizational readiness (Jewapatarakul & Ueasangkomsate, 2024; Saptaningtyas & Rahayu, 2020). Broader Industry 4.0-food reviews also caution that trust, adaptability, and economic uncertainty remain barriers for lower-resource enterprises (Yap & Al-Mutairi, 2024).

Designing measurement around these multiple dimensions can reveal whether an intervention creates a resilient production capability or only a temporary increase in machine output.

Limitations and future research

Several limitations constrain inference. First, the study involved a single enterprise and no concurrent control site. Before-and-after changes may therefore include effects from demand, learning, management attention, or other contextual factors. Second, many system-level outcomes were available only as aggregated observations. Inferential analysis was possible for product dimensions, mass, compliance, and package leakage because sample size and dispersion or counts were reported, but statistical significance was not inferred for process time, hygiene scores, consumer means, or business outcomes where individual or repeated-measure variance was unavailable. Third, the four-week follow-up established initial adoption but cannot demonstrate long-term equipment reliability, maintenance economics, behavioral persistence, or data discipline.

Fourth, hygiene assessment was based on audit and behavior indicators rather than full microbiological validation. Future work should combine GMP/SSOP audits with surface, product, and water microbiology and formal shelf-life testing. Fifth, the consumer evaluation was local and lacked individual-level variance and segmentation in the available dataset. Larger studies should test whether responses differ by age, purchasing channel, health orientation, and prior familiarity with the brand.

Future research should evaluate Granoformix or comparable appropriate-scale systems across multiple food MSMEs using prospective, repeated batch-level measurement. Matched-control or stepped-wedge implementation could help separate technology effects from time trends. Digital logs could support statistical process control, process-capability indices, downtime analysis, and maintenance modeling, while energy and resource measurements could test sustainability claims more directly. More advanced analytics may eventually be useful, as suggested by smart-manufacturing and data-driven food-processing studies (Hassani et al., 2025; Raut et al., 2022), but the present case indicates that the first priority is a reliable, maintainable data foundation. Long-term economic evaluation should also include capital recovery, total cost of ownership, spare parts, operator training, and sensitivity to production volume. Such work would test whether the integrated model observed here is transferable and would clarify the boundary conditions under which appropriate-scale automation creates durable value for resource-constrained food enterprises.

CONCLUSION

The Granoformix field implementation transformed a fragmented semi-manual granola-bar process into a more integrated, standardized, and traceable micro-production system. For a constant 10-kg reference batch, production time decreased from 318 to 205 min while output increased from 320 to 430 bars. These efficiency gains were accompanied by improved product conformity rather than a quality trade-off: dimensional compliance increased from 66% to 95%, weight compliance from 68% to 96%, and defect rate decreased from 10.0% to 3.3%. Hygiene performance improved through the combination of reduced manual contact, one-way flow, GMP/SSOP, and operator training. Digital documentation reached 96.1% completeness and enabled faster batch traceability, while improved packaging and more consistent products were accompanied by stronger consumer ratings and favorable business indicators.

The central contribution of the study is therefore not simply the demonstration that an automated machine can increase throughput. The evidence supports a broader model in which appropriate-scale automation acts as the physical core of a socio-technical production system linking process control, sanitation, workforce capability, documentation, traceability, and market communication. In this setting, the integration of these elements allowed operational, quality, hygiene, and commercial indicators to improve concurrently.

Because the evidence derives from a single MSME and several outcomes are available only as aggregate before-and-after measures, the magnitude of the observed effects should not be generalized uncritically. Multisite, longer-term studies with raw batch-level data, microbiological validation, and formal economic analysis are needed. Nevertheless, the present results provide field evidence that integrated, maintainable, and data-supported automation can offer a practical pathway for modernization of resource-constrained food MSMEs.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Lembaga Penelitian dan Pengabdian kepada Masyarakat Universitas Negeri Malang (LPPM UM) for providing financial support for this study. The authors also thank Bawang Goreng Bangor Kediri and its production team for facilitating access to the field setting, supporting the implementation of the Fryonix system, and assisting with operational data collection.

REFERENCES

- Abaker, A. A. (2025). Decentralized Supply Chain Management: A Blockchain Framework for Transparency and Traceability. In Hussain O.K., Alsaleem S., Ma S.-P., Lu X., & Chao K.-M. (Eds.), *Proc. - IEEE Int. Conf. E-Bus. Eng., ICEBE* (pp. 235–241). Institute of Electrical and Electronics Engineers Inc. <https://doi.org/10.1109/ICEBE68123.2025.00044>
- Abdul Wahab, D., Dewi Anggadini, S., Sulistiyo Soegoto, D., & Yunanto, R. (2024). Building the success of culinary SMEs in food processing: Perspectives on business ecosystem analysis and digital transformation in West Java, Indonesia. *Edelweiss Applied Science and Technology*, 8(6), 8281–8293. <https://doi.org/10.55214/25768484.v8i6.3791>
- Accorsi, R., Tufano, A., Gallo, A., Galizia, F. G., Cocchi, G., Ronzoni, M., Abbate, A., & Manzini, R. (2019). An application of collaborative robots in a food production facility. In Ryan A., Gordon S., & Tiernan P. (Eds.), *Procedia Manuf.* (Vol. 38, pp. 341–348). Elsevier B.V. <https://doi.org/10.1016/j.promfg.2020.01.044>
- Aggogeri, F., Pellegrini, N., & Taesi, C. (2024). Towards industrial robots' maturity: An Italian case study. *Robotics*, 13(3), 42. <https://doi.org/10.3390/robotics13030042>
- Amirkhanova, G., Adilkyzy, S., Amirkhanov, B., Baizhanova, D., & Chen, S. (2026). A Digital Twin Architecture for Integrating Lean Manufacturing with Industrial IoT and Predictive Analytics. *Information (Switzerland)*, 17(2). <https://doi.org/10.3390/info17020196>
- Anggrahini, D., Prasetyawan, Y., & Diartiwi, S. I. (2020). Increasing production efficiency using karakuri principle (a case study in small and medium enterprise). *IOP Conf. Ser. Mater. Sci. Eng.*, 852(1). <https://doi.org/10.1088/1757-899X/852/1/012117>
- Arena, S., Cinus, A., Deias, A., Lera, M., Piloni, M. T., & Orrù, P. F. (2023). Industry 4.0 assessment in agri-food and dairy sector: A literature review of Maturity Models. *Proc. Summer Sch. Francesco Turco. Proceedings of the Summer School Francesco Turco*. <https://www.scopus.com/pages/publications/85193758293?origin=resultslist>
- Aviles-Sacoto, S. V., Velasco-Tapia, K. C., Aviles-Sacoto, E. C., & Arguello-Herrera, J. I. (2024). Innovating for impact: Proposing Quality 4.0 integration to achieve sustainable development goals in microenterprises. *Business Strategy & Development*, 7(2). <https://doi.org/10.1002/bsd2.371>
- Baek, S., Oh, S. E., Lee, S. H., & Kwon, K. H. (2024). A Simulation-Based Approach for Evaluating the Effectiveness of Robotic Automation Systems in HMR Product Loading. *Foods*, 13(19). <https://doi.org/10.3390/foods13193121>
- Basar, M. F., Farriz, N. I. B. M., Hasim, N., & Aliteh, N. A. (2025). Design and Development of an Automated Wrapper Machine for Roasted Glutinous Rice. *International Journal of Engineering Trends and Technology*, 73(12), 84–94. <https://doi.org/10.14445/22315381/IJETT-V73I12P108>
- Chandrayan, B., Gupta, S., Kumar, R., Dangayach, G. S., & Jagtap, S. (2023). Modelling and analysis of key enablers of digital transformation in food SMEs using ISM and MICMAC approach. *International Journal of Intelligent Enterprise*, 10(4), 419–444. <https://doi.org/10.1504/IJIE.2023.133826>
- Coito, T., Firme, B., Martins, M. S. E., Vieira, S. M., Figueiredo, J., & Sousa, J. M. C. (2021). Intelligent sensors for real-time decision-making. *Automation*, 2(2), 62–82. <https://doi.org/10.3390/automation2020004>
- Dahm, M., & Mathur, A. (1990). Automation in the food processing industry: Distributed control systems. *Food Control*, 1(1), 32–35. [https://doi.org/10.1016/0956-7135\(90\)90118-V](https://doi.org/10.1016/0956-7135(90)90118-V)
- Frau, M., Moi, L., & Cabiddu, F. (2022). Digital Transformation Through the Lens of Digital Data Handling: An Exploratory Analysis of Agri-Food SMEs. *Journal of Small Business Strategy*, 32(3), 84–97. <https://doi.org/10.53703/001c.34642>

- Griffin, S. J., Hull, J. B., & Lai, E. (2001). Development of a novel ultrasound monitoring system for container filling operations. *Journal of Materials Processing Technology*, 109(1–2), 72–77. [https://doi.org/10.1016/S0924-0136\(00\)00777-9](https://doi.org/10.1016/S0924-0136(00)00777-9)
- Hassani, A., Alami, I., & Andaloussi, Z. E. (2025). From Data to Sustainability: Exploring the role of Big Data Analytics. *Int. Conf. Artif. Intell. Comput., Data Sci., Appl., ACDSA. International Conference on Artificial Intelligence, Computer, Data Sciences, and Applications, ACDSA 2025*. <https://doi.org/10.1109/ACDSA65407.2025.11165852>
- Ismail, S., Reza, H., Salameh, K., Zadeh, H. K., & Vasefi, F. (2023). Toward an intelligent blockchain IoT-enabled fish supply chain: A review and conceptual framework. *Sensors*, 23(11), 5136. <https://doi.org/10.3390/s23115136>
- Jewapatarakul, D., & Ueasangkomsate, P. (2024). Digital Organizational Culture, Organizational Readiness, and Knowledge Acquisition Affecting Digital Transformation in SMEs from Food Manufacturing Sector. *SAGE Open*, 14(4). <https://doi.org/10.1177/21582440241297405>
- Kang, Y., & Park, D. (2026). Operational Data Foundation Framework for Smart Manufacturing in SMEs: Field Implementation and Evaluation. *Systems*, 14(5). <https://doi.org/10.3390/systems14050515>
- Khan, Z., Khalid, A., & Iqbal, J. (2018). Towards realizing robotic potential in future intelligent food manufacturing systems. *Innovative Food Science & Emerging Technologies*, 48, 11–24. <https://doi.org/10.1016/j.ifset.2018.05.011>
- Komori-Zevallos, A. R., Montedoro-Garay, F. M., Garcia-Lopez, Y. J., & Flores, J. C. Q. (2023). A Production Model That Combines Lean And Industry 4.0 Principles To Enhance The Productivity Of Small And Medium-Sized Enterprises (SMEs) In Peru's Food Manufacturing Sector. In Herberger D. & Hubner M. (Eds.), *Proc. Conf. Prod. Syst. Logist.* (pp. 139–150). Publish-Ing in cooperation with TIB - Leibniz Information Centre for Science and Technology University Library. <https://doi.org/10.15488/15256>
- Konur, S., Lan, Y., Thakker, D., Morkyani, G., Polovina, N., & Sharp, J. (2023). Towards design and implementation of Industry 4.0 for food manufacturing. *Neural Computing and Applications*, 35(33), 23753–23765. <https://doi.org/10.1007/s00521-021-05726-z>
- Kotsilitis, S., Chairetakis, K., Katsari, A., & Marcoulaki, E. (2020a). The supremo experiment for smart monitoring for energy efficiency and predictive maintenance of electric motor systems. In Baraldi P., Di Maio F., & Zio E. (Eds.), *Proc. Eur. Saf. Reliab. Conf. Probab. Saf. Assess. Manag. Conf.* (pp. 3415–3422). Research Publishing, Singapore. https://doi.org/10.3850/978-981-14-8593-0_4047-cd
- Laghough, A., Zafrah, F. B., Qureshi, M. N., & Sahli, A. A. (2024). Eliminating non-value-added activities and optimizing manufacturing processes using process mining: A stock of challenges for family SMEs. *Sustainability*, 16(4), 1694. <https://doi.org/10.3390/su16041694>
- Lv, G., Song, C., Xu, P., Qi, Z., Song, H., & Liu, Y. (2023). Blockchain-based traceability for agricultural products: A systematic literature review. *Agriculture*, 13(9), 1757. <https://doi.org/10.3390/agriculture13091757>
- Madhavan, M., Sharafuddin, M. A., & Wangtueai, S. (2024). Measuring the Industry 5.0-Readiness Level of SMEs Using Industry 1.0–5.0 Practices: The Case of the Seafood Processing Industry. *Sustainability (Switzerland)*, 16(5). <https://doi.org/10.3390/su16052205>
- Malavi, D., Abong, G., & Muzhingi, T. (2021). Effect of food safety training on behavior change of food handlers: A case of orange-fleshed sweetpotato puree processing in Kenya. *Food Control*, 119, 107500. <https://doi.org/10.1016/j.foodcont.2020.107500>
- Malavi, D., Muzhingi, T., & Abong, G. (2018). Good manufacturing practices and microbial contamination sources in orange-fleshed sweet potato puree processing plant in Kenya. *International Journal of Food Science*, 2018, 1–11. <https://doi.org/10.1155/2018/4093161>
- Martinravi, C. P., & Krishnasamy, K. (2025). Unleashing the potential of MSMEs in India: A strategic analysis. *Journal of the International Council for Small Business*, 6(1), 123–143. <https://doi.org/10.1080/26437015.2024.2397664>
- Mashoko, D. (2025). Disruptive Frugal Digital Technology and Small and Medium Enterprises' Innovation Performance in the Food Sector in Zimbabwe: A Case of SMEs in Masvingo Urban.

- Disruptive Frugal Digital Innovation in Africa, 223–244. <https://doi.org/10.1108/978-1-83549-568-120251013>
- Musa, S. F. P. D., Haji Besar, M. H. A., & Anshari, M. (2023). COVID-19, local food system and digitalisation of the agri-food sector. *Journal of Indian Business Research*, 15(1), 125–140. <https://doi.org/10.1108/JIBR-04-2022-0103>
- Nasirinejad, M., Afshari, H., & Sampalli, S. (2026). The adoption of digital twin technologies for maintenance in small and medium-sized enterprises: Challenges and benefits. *Advanced Engineering Informatics*, 74. <https://doi.org/10.1016/j.aei.2026.104645>
- Pech, M., Vrchota, J., & Bednar, J. (2021). Predictive maintenance and intelligent sensors in smart factory: Review. *Sensors*, 21(4), 1470. <https://doi.org/10.3390/s21041470>
- Raffik, R., Roshan, R. P., Subash, C., & Sanjeev, K. B. (2023). Role of Robotics and Automation in Food Industries: An Overview. *Int. Conf. Adv. Electr., Electron., Commun., Comput. Autom., ICAECA. 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation, ICAECA 2023*. <https://doi.org/10.1109/ICAECA56562.2023.10199301>
- Ranjini, V. K., Gururaja, B. L., & Rajewari, P. S. (2025). Role of Digital Transformation on Green Innovation and Sustainability in Food Processing MSMEs: A Review. *Proc. Int. Conf. Comput. Sustain. Glob. Dev., INDIACom. Proceedings of the 2025 12th International Conference on Computing for Sustainable Global Development, INDIACom 2025*. <https://doi.org/10.23919/INDIACom66777.2025.11115666>
- Raut, S., von Gersdorff, G., Schemminger, J., Adolphs, J., & Sturm, B. (2022). Improving food processing through integration of artificial intelligence in the drying process: A perspective. In Gandorfer M., Hoffmann C., El Benni N., Cockburn M., Anken T., & Floto H. (Eds.), *Lect. Notes Informatics (LNI), Proc. - Series Ges. Inform. (GI): P-317* (pp. 231–236). Gesellschaft fur Informatik (GI). <https://www.scopus.com/pages/publications/85128170624?origin=resultslist>
- Rivera, M. J. S., Hadji Yassin, N. A., Queddeng, J. D., & Robielos, R. A. C. (2020). Impact assessment on dost small enterprise technology upgrading program (Setup) – assisted msme using analytic hierarchy (ahp) model. *Proc. Int. Conf. Ind. Eng. Oper. Manage., (August)*. <https://www.scopus.com/pages/publications/85096611621?origin=resultslist>
- Samara, I., Almohtaseb, A., & Aldehayyat, J. (2026). Strategic CSR and digital transformation: Pathways to SME performance in a turbulent emerging market. *Journal of Strategy and Management*, 1–26. <https://doi.org/10.1108/JSMA-10-2025-0391>
- Sánchez-Rodríguez, A., Ullrich-Estrella, R. D., González-Gallardo, C. E., Jácome-Villacres, M. B., García-Vidal, G., & Pérez-Campdesuñer, R. (2025). Deep Learning-Based Digital, Hyperspectral, and Near-Infrared (NIR) Imaging for Process-Level Quality Control in Ecuador's Agri-Food Industry: An ISO-Aligned Framework. *Processes*, 13(11). <https://doi.org/10.3390/pr13113544>
- Saptaningtyas, W. W. E., & Rahayu, D. K. (2020). A proposed model for food manufacturing in smes: Facing industry 5.0. *Proc. Int. Conf. Ind. Eng. Oper. Manage., (August)*. <https://www.scopus.com/pages/publications/85096609029?origin=resultslist>
- Taha, N. F. M. (2026). Robotics as a Catalyst for Sustainable Food Manufacturing: A Malaysian Empirical Study. *Applied Research*, 5(1). <https://doi.org/10.1002/appl.70077>
- Urban, W., Łukaszewicz, K., & Krawczyk-Dembicka, E. (2020). Application of industry 4.0 to the product development process in project-type production. *Energies*, 13(21). <https://doi.org/10.3390/en13215553>
- Valles, J., Vasquez, G., & Hurtado, A. (2025). Smart manufacturing for snacks: Integrating SMED, predictive maintenance, line balancing, IoT, and machine learning to improve efficiency. In Zhang C. (Ed.), *Proc SPIE Int Soc Opt Eng (Vol. 13977)*. SPIE. <https://doi.org/10.1117/12.3091071>
- Wang, C.-Y., Chen, Y.-J., & Chien, C.-F. (2021). Industry 3.5 to empower smart production for poultry farming and an empirical study for broiler live weight prediction. *Computers and Industrial Engineering*, 151. <https://doi.org/10.1016/j.cie.2020.106931>
- Yap, C. K., & Al-Mutairi, K. A. (2024). A Conceptual Model Relationship between Industry 4.0—Food-Agriculture Nexus and Agroecosystem: A Literature Review and Knowledge Gaps. *Foods*, 13(1). <https://doi.org/10.3390/foods13010150>