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Proposed Improvement of Sodium Sulfate Storage System to Minimize Caking Defects Using DMAIC and FMEA Methods

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ABSTRACT

Sodium sulfate is a critical raw material in the glass industry that is highly susceptible to caking defects during storage due to its hygroscopic nature. This study aims to analyze the occurrence of caking defects and develop improvement strategies for the sodium sulfate storage system in the logistics department of PT XYZ. The Six Sigma approach was implemented through the DMAIC framework, integrated with Failure Mode and Effect Analysis (FMEA) and a proportion control chart (p-chart). Based on September 2025 operational data, 71 out of 294 received tons experienced caking defects, yielding an average defect proportion of 24.15%. A DPMO value of 241,500 indicated a process capability of 2.20 sigma, which falls below industrial quality standards. The p-chart revealed that the process was statistically unstable. Root cause analysis identified five contributing factors: material, environment, method, human resources, and measurement. FMEA highlighted the most critical risks as high warehouse relative humidity (RPN 448), inadequate inspection procedures (RPN 336), three-tier stacking (RPN 288), and excessive storage duration (RPN 150). Proposed improvements include humidity control, enhanced inspection procedures, two-tier stacking limitation, and FIFO system implementation to reduce storage-related defects and improve overall operational quality performance.
Keyword: *Caking Defect, DMAIC, FMEA, Six Sigma, Sodium Sulfate*

ABSTRAK

Sodium sulfat merupakan bahan baku penting dalam industri kaca yang sangat rentan mengalami cacat caking selama penyimpanan akibat sifat higroskopisnya. Penelitian ini bertujuan untuk menganalisis terjadinya cacat caking serta mengembangkan strategi perbaikan sistem penyimpanan sodium sulfat di departemen logistik PT XYZ. Pendekatan Six Sigma diterapkan melalui kerangka DMAIC yang diintegrasikan dengan Failure Mode and Effect Analysis (FMEA) dan peta kendali proporsi (p-chart). Berdasarkan data operasional September 2025, sebanyak 71 dari 294 ton material yang diterima mengalami cacat caking dengan rata-rata proporsi cacat sebesar 24,15%. Nilai DPMO sebesar 241.500 menunjukkan kapabilitas proses berada pada level 2,20 sigma yang masih berada di bawah standar kualitas industri. Hasil p-chart menunjukkan bahwa proses berada dalam kondisi tidak stabil secara statistik. Analisis akar penyebab mengidentifikasi lima faktor utama, yaitu material, lingkungan, metode, sumber daya manusia, dan pengukuran. Hasil FMEA menunjukkan risiko paling kritis berasal dari kelembapan relatif gudang yang tinggi (RPN 448), prosedur inspeksi yang tidak memadai (RPN 336), penumpukan tiga lapis (RPN 288), serta durasi penyimpanan yang terlalu lama (RPN 150). Usulan perbaikan meliputi pengendalian kelembapan, peningkatan prosedur inspeksi, pembatasan penumpukan menjadi dua lapis, serta penerapan sistem FIFO untuk mengurangi cacat akibat penyimpanan dan meningkatkan kinerja kualitas operasional secara keseluruhan.
Keyword: *Caking Defect, DMAIC, FMEA, Six Sigma, Sodium Sulfat*

1. Introduction

The glass manufacturing industry operates as a continuous process that demands a reliable supply of raw materials to sustain uninterrupted production. In continuous manufacturing systems, any disruption to the physical condition of raw materials directly affects process performance and downstream quality outcomes [1], [2]. Sodium sulfate serves as an important auxiliary material in glass composition, supporting the refining and melt stabilization process. Quality control of raw materials therefore extends beyond chemical specification compliance to include maintaining the physical condition of materials throughout the storage and logistics chain, as instability in raw material condition can propagate losses across the entire production system [3], [4].

Powder materials with hygroscopic properties are particularly susceptible to environmental exposure during storage. When relative humidity (RH) exceeds a critical threshold, moisture absorption initiates liquid bridge formation and surface recrystallization, which strengthens interparticle cohesion and progressively reduces flowability [5], [6]. The sensitivity of inorganic salts such as sodium sulfate to humidity is further confirmed by the phase behavior observed near their deliquescence point, where even metastable phases contribute to moisture uptake [7]. Prolonged storage under mechanical load compounds this process, as consolidation pressure accelerates caking in hygroscopic powder materials [8], [9]. Similar caking behavior has been reported across a range of powder types, including food-grade and inorganic materials, confirming that storage environment control is a broadly critical factor for maintaining powder physical performance [10], [11].

These phenomena manifest directly in the sodium sulfate storage system of the logistics department at PT XYZ. Based on inspection data from September 2025, significant fluctuations in caking defect proportions were observed across material receipt batches, with some periods recording defect rates above 70%. However, moisture content test results for all samples remained below the company maximum specification of 0.1%, indicating that factors beyond moisture content alone, including warehouse RH, temperature, storage duration, and stacking configuration, drive defect formation in this context. When caking defects occur at scale, they generate direct operational losses including extended feeding time, additional manual labor for breaking agglomerates, and potential material return to the supplier [2], [12]. If left uncontrolled, such defects become a recurring source of process variability that undermines the reliability of the supply chain feeding continuous production [1].

The Six Sigma DMAIC framework has been widely validated as a structured, data-driven approach to defect identification and reduction across diverse manufacturing and logistics contexts. In manufacturing quality improvement, prior studies covering industries such as stamping, vehicle components, packaging, book printing, sewing process and general production have confirmed the consistent effectiveness of DMAIC in reducing defect rates [13], [14], [15], [16], [17], [18], [19]. For powder and granular materials specifically, DMAIC combined with Failure Mode and Effect Analysis (FMEA) has demonstrated systematic root cause identification and risk prioritization in studies on surfactant powder, powdered beverages, wood powder, animal feed, and sachet [20], [21], [22], [23], [24], [25], [26], [27].

The FMEA framework assigns Severity, Occurrence, and Detection ratings to calculate a Risk Priority Number (RPN), providing a structured basis for prioritizing corrective actions across failure modes [28], [29], [30]. In logistics and inventory contexts, Six Sigma DMAIC has further shown effectiveness in improving stock control accuracy and reducing non-value-added activities in storage operations [31], [32]. However, most prior studies address production-stage defects rather than defects arising from raw material storage conditions before materials enter the production line. Studies focusing specifically on hygroscopic powder degradation during pre-production storage, and integrating both risk prioritization and statistical process monitoring within a single control framework, remain limited in the literature.

Unlike previous studies that predominantly focus on production-stage defects, this study integrates DMAIC, FMEA, and p-chart analysis to evaluate storage-induced caking defects in hygroscopic inorganic raw materials within a continuous glass manufacturing environment. This study therefore aims to analyze the caking defect rate of sodium sulfate at PT XYZ and propose an improved storage control system, contributing a practical framework for pre-production raw material quality management applicable to similar continuous manufacturing settings.

2. Method

This study employs a quantitative descriptive approach to analyze sodium sulfate caking defects and design an improved storage control system in the logistics department of PT XYZ, a continuous glass manufacturing company. The research was conducted during a field internship period in September 2025 and is structured according to the Six Sigma DMAIC framework.

2.1. Research Object

The research object is the sodium sulfate storage system in the raw material warehouse of the logistics department at PT XYZ. The study focuses on the caking defect phenomenon occurring during the pre-production storage period before the material is fed into the glass production hopper. Observations were directed at the warehouse storage area, covering stacking configuration, environmental conditions, storage duration, and material handling procedures.

2.2. Data Collection

Data were collected through three methods. First, direct observation was conducted in the sodium sulfate storage area to obtain an actual picture of stacking configurations, warehouse layout, and environmental conditions that potentially influence caking defect formation. Second, a semi-structured interview was conducted with one key informant, namely the Section Head of Raw Materials, selected through purposive sampling due to direct responsibility for warehouse operations. The interview was aimed at obtaining information regarding material receiving procedures, storage systems, quality inspection methods, and handling of defective materials. Third, documentation was performed by collecting historical company data for the September 2025 observation period from the logistics department archive system. Secondary data collected included: total sodium sulfate tonnage received per batch, defect data per batch (caking tonnage Not OK and accepted tonnage OK), moisture content test results from the Quality Assurance department, warehouse relative humidity (RH) and temperature records, and storage duration data per arrival batch.

2.3. Data Processing

Data processing was carried out in two streams. Quantitative processing included: recapitulation of material arrivals and defect quantities per period, calculation of defect proportion per batch, identification of Critical to Quality (CTQ), calculation of Defect per Opportunity (DPO) using Equation (1), Defect per Million Opportunities (DPMO) using Equation (2), sigma level using Equation (3), and process yield. A proportion control chart (p-chart) was constructed including calculation of Upper Control Limit (UCL) and Lower Control Limit (LCL) using Equations (4) and (5), and identification of out-of-control observation points. Risk Priority Number (RPN) was calculated based on Severity (S), Occurrence (O), and Detection (D) scores using Equation (6). The S, O, and D scoring criteria followed the standard 1 to 10 FMEA scale adapted from The Basics of FMEA [28]and validated through expert judgment with the Section Head of Raw Materials. Qualitative processing included: construction of a SIPOC diagram to map the sodium sulfate storage process from supplier through production feeding, cause-and-effect analysis using a fishbone diagram to identify potential contributing factors across five categories (Materials, Environment, Methods, Man, and Measure), and Failure Mode and Effect Analysis (FMEA) to systematically evaluate failure modes and prioritize corrective actions.

2.4. Analysis Framework: Six Sigma DMAIC

The analytical framework follows the five stages of the Six Sigma DMAIC cycle applied sequentially. In the Define stage, the problem scope and Critical to Quality (CTQ) characteristic were established, and a SIPOC diagram was constructed to map the storage process. In the Measure stage, process performance was quantified using DPO, DPMO, sigma level, and process yield based on actual defect data, and a p-chart was used to evaluate statistical stability. In the Analyze stage, potential root causes were identified through fishbone diagram analysis, followed by FMEA to assign RPN values and prioritize failure modes for corrective action. In the Improve stage, four improvement proposals were formulated based on RPN priority, covering warehouse RH control, material receiving inspection procedures, stacking configuration management, and a FIFO stock management system. In the Control stage, a proposed monitoring and sustainability plan was designed, including SOPs, operational control forms, and a periodic internal audit schedule.

3. Result and Discussion

3.1. Define Stage

The Define stage established the main problem, its operational impacts, and the quality characteristic to be controlled. Based on inspection data from September 2025 at PT XYZ, significant fluctuations in caking defect

proportion were observed across material receipt batches, with defect rates ranging from 0% to 82%. Despite all moisture content test results remaining below the company maximum specification of 0.1%, caking defects still occurred at substantial levels, indicating that factors beyond moisture content alone drive defect formation during storage.

The operational impacts of caking defects were identified as threefold. First, caking prevents free-flowing material behavior during hopper feeding, requiring manual breaking of agglomerates before the material can enter the production system. Second, heavily caked material batches are returned to the supplier, causing additional coordination costs and potential disruption to raw material supply continuity. Third, the manual breaking activity constitutes a non-value-added operation that increases handling time, reduces operator productivity, and threatens the continuity of the continuous glass manufacturing process [2].

Based on these impacts, one Critical to Quality (CTQ) was identified: the absence of caking defect in sodium sulfate during storage, measured as the proportion of Not OK tonnage against total tonnage received per batch. The target is a caking defect proportion of 0%. Table 1 presents the CTQ identification.

Table 1. CTQ Identification for Sodium Sulfate Caking Defect

No	Quality Dimension	CTQ	Defect Definition	Measurement Method	Unit	Target
1	Physical condition of material	Material free from caking defect during storage	Material declared Not OK when agglomeration prevents free-flowing behavior during production feeding	Not OK tonnage due to caking vs. total received tonnage per period	Percentage (%)	0%

The SIPOC diagram (Table 2) maps the sodium sulfate storage process from supplier to production, confirming that the warehouse storage stage is the critical control point where defect formation occurs before material enters the production line.

Table 2. SIPOC Diagram of Sodium Sulfate Storage Process at PT XYZ

Supplier	Input	Process	Output	Customer
Sodium sulfate suppliers	Sodium sulfate in jumbo bag packaging; receiving documents; material quality specifications	(1) Material receiving at warehouse; (2) Physical condition inspection; (3) Storage in warehouse area; (4) Material release for production feeding	OK material (meets specification); Not OK material (caking defect); Material status information	Production Department (Batching Plant) uses material for mixing and melting process

3.2. Measure Stage

The Measure stage quantified process performance using actual defect data from September 2025. Table 3 presents the complete defect recapitulation across all eight observation batches.

Table 3. Sodium Sulfate Defect Recapitulation September 2025, PT XYZ

No.	Date	Total Received (ton)	Ok (Ton)	Not Ok (Ton)	Caking (%)
1	13/09/2025	48	47	1	2%
2	14/09/2025	30	24	6	20%
3	18/09/2025	25	7	18	72%
4	19/09/2025	30	29	1	3%
5	20/09/2025	25	21	4	16%
6	25/09/2025	51	51	0	0%
7	26/09/2025	35	35	0	0%

No.	Date	Total Received (ton)	Ok (Ton)	Not Ok (Ton)	Caking (%)
8	27/09/2025	50	9	41	82%
Total		294	223	71	24,15%

Process capability metrics were calculated as follows. The average defect proportion ($\bar{p}$) was 71/294 = 0.2415, or 24.15%. With one CTQ opportunity per ton of material, DPO = 0.2415 and DPMO = 241,500. Converting DPMO to sigma level using standard sigma conversion tables, the process operates at approximately 2.20 sigma. Process yield was calculated as 75.85%. These results indicate that the storage process is operating at a low capability level, significantly below world-class Six Sigma performance [25].

Table 4. P-Chart Data, Proportion Control Limits per Observation Period

No	Date	n (ton)	Not OK (ton)	Proportion (p)	CL ($\bar{p}$)	UCL	LCL	Status
1	13/09/2025	48	1	0.0208	0.2415	0.4268	0.0562	Out of Control
2	14/09/2025	30	6	0.2	0.2415	0.4759	0.0071	In Control
3	18/09/2025	25	18	0.72	0.2415	0.4983	0	Out of Control
4	19/09/2025	30	1	0.0333	0.2415	0.4759	0.0071	In Control
5	20/09/2025	25	4	0.16	0.2415	0.4983	0	In Control
6	25/09/2025	51	0	0	0.2415	0.4213	0.0617	Out of Control
7	26/09/2025	35	0	0	0.2415	0.4585	0.0245	Out of Control
8	27/09/2025	50	41	0.82	0.2415	0.4231	0.0599	Out of Control

Five out of eight observation points were identified as out-of-control. Observations 3 and 8 exceeded the UCL, recording caking proportions of 0.72 and 0.82 respectively, indicating severely elevated defect rates attributable to special causes. Observations 1, 6, and 7 fell below the LCL, recording defect proportions of 0.0208, 0.00, and 0.00 respectively. Although observations below the LCL indicate lower defect proportions, they are statistically classified as special-cause variation because they deviate significantly from the historical process average, suggesting that batch-specific favorable conditions, most likely shorter storage durations or temporarily lower RH exposure at the time of feeding, produced atypically low defect rates rather than reflecting stable process performance. This extreme bimodal variation pattern confirms that the storage process is not in a state of statistical control and that defect variability is driven by special causes rather than random variation.

3.3. Analyze Stage

3.3.1. Fishbone Diagram Analysis

Root cause analysis using a fishbone diagram identified potential contributing factors to caking defect formation across five categories. In the Materials category, the hygroscopic nature of sodium sulfate was identified as the fundamental material characteristic that makes it inherently susceptible to moisture absorption and interparticle agglomeration under elevated humidity conditions [11]. Additionally, non-uniform moisture distribution within jumbo bag packaging means that sampling-based moisture content testing may not capture the actual condition of the entire batch.

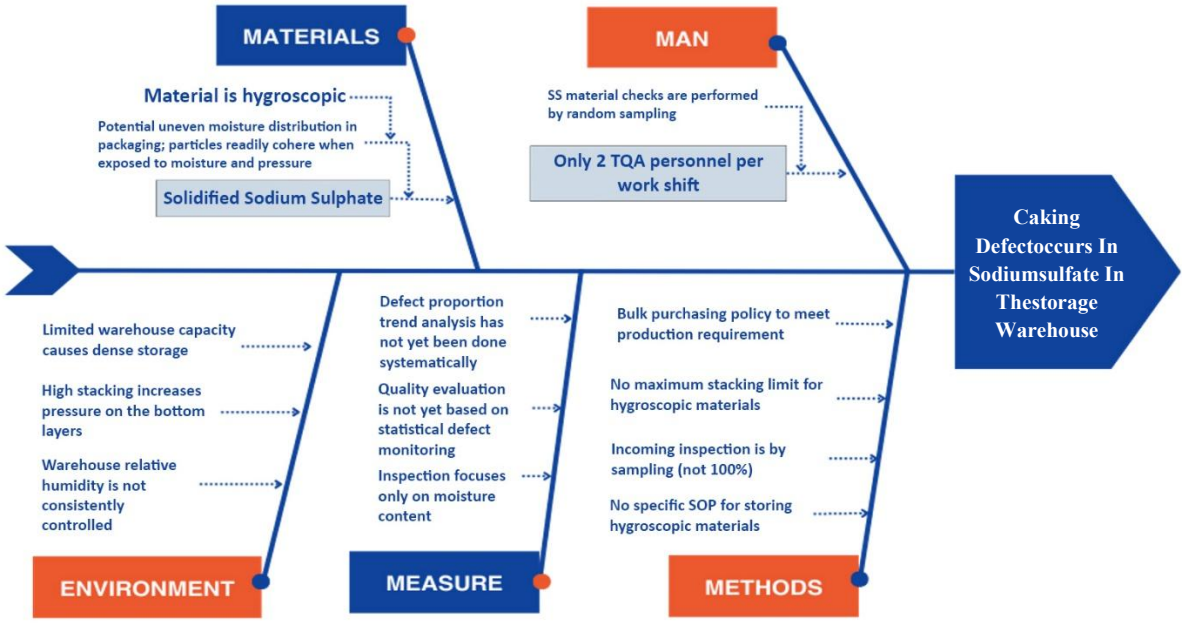


Figure 1. Fishbone Diagram

In the Environment category, warehouse RH consistently exceeding 60% was identified as the dominant environmental factor. All eight observation periods at PT XYZ recorded RH above 60%, ranging from 63.0% to 74.4%, while warehouse temperature ranged between 27.6°C and 30.0°C. The absence of an active humidity control system means that warehouse conditions are directly influenced by external weather, with higher RH levels recorded during rainy season conditions [9]. The three-tier stacking system further contributes to defect formation by imposing mechanical pressure of approximately 2 tons on the lowest layer, accelerating particle compaction when combined with elevated humidity exposure.

In the Methods category, large volume deliveries of approximately 30 jumbo bags per truck create storage periods extending beyond the ideal 1 to 2 days. The absence of a specific SOP for hygroscopic material storage means there is no standardized procedure for humidity control or material rotation. In the Man category, the high delivery volume makes comprehensive inspection of all units impractical, resulting in a visual sampling approach that leaves a substantial portion of each batch uninspected. In the Measure category, the absence of systematic statistical monitoring of defect trends means that emerging patterns in defect rates go undetected until the problem reaches a critical level.

3.3.2. FMEA Analysis

Based on the fishbone analysis, four failure modes were identified and evaluated using FMEA. Table 5 presents the complete results including Severity, Occurrence, and Detection ratings, RPN values, and priority ranking.

Table 5. FMEA Results, Sodium Sulfate Storage System at PT XYZ

No	Potential Failure Mode	Potential Effect	S	Potential Cause	O	Current Control	D	RPN	Priority
1	High warehouse RH (>60%)	Material absorbs moisture, forms hard agglomerates, impedes production feeding, requires manual breaking	8	No active humidity control system; warehouse conditions influenced by external weather	8	RH monitoring using hygrometer without automatic control or corrective action trigger	7	448	1

No	Potential Failure Mode	Potential Effect	S	Potential Cause	O	Current Control	D	RPN	Priority
2	Incomplete inspection (visual sampling only)	Caked material passes receiving inspection and is only detected during production feeding, causing unplanned downtime	7	Sampling-based inspection only; large delivery volume of approximately 30 jumbo bags per truck	6	Visual inspection during material receiving	8	336	2
3	Three-tier stacking system	Mechanical pressure accelerates particle compaction and worsens agglomerate hardness	6	Limited warehouse capacity; standard practice of 3-tier stacking	8	Visual observation of stacking height	6	288	3
4	Storage duration approaching or reaching critical limit (4 days or more)	Prolonged humidity exposure increases agglomeration risk and potential flow obstruction during feeding	6	Two of eight batches (25%) reached the 4-day critical limit; no FIFO system or automatic duration alert	5	Arrival date recorded in inventory system	5	150	4

The highest RPN value of 448 was obtained for high warehouse RH, assigned Severity = 8 due to its direct and significant operational impact, Occurrence = 8 because RH consistently exceeded 60% across all eight observations with no active control system, and Detection = 7 because although hygrometer readings are available, the absence of an automatic corrective response means the information does not effectively prevent defect formation. This finding aligns with literature confirming that hygroscopic inorganic materials undergo accelerated caking under sustained elevated humidity [5], [8]. The incomplete inspection mechanism ranked second (RPN = 336) with the highest Detection score (D = 8), reflecting the structural inability of visual sampling to detect internal caking within sealed jumbo bags, substantiated by empirical cases at PT XYZ where materials passing receiving inspection were found caked during production feeding. The three-tier stacking configuration ranked third (RPN = 288) with the highest Occurrence score (O = 8), as this practice is applied routinely in all storage cycles due to warehouse capacity constraints. Storage duration ranked fourth (RPN = 150), reflecting a moderate risk level consistent with the observation that no batches exceeded 4 days during the study period, though 25% reached that threshold exactly.

3.4. Improve Stage

Four improvement proposals were formulated based on RPN priority, each targeting the Occurrence and Detection parameters identified in the FMEA analysis.

a. Improvement 1: Warehouse RH Control SOP (RPN = 448). A Standard Operating Procedure for relative humidity control was designed, establishing a maximum RH threshold of 60% during operational storage hours at PT XYZ. The SOP requires a minimum of three RH monitoring sessions per shift using a calibrated digital hygrometer, documented in a daily control form. Corrective actions for RH above 60% include opening supplementary ventilation for at least 30 minutes, activating available dehumidifiers,

limiting warehouse door opening frequency, and escalating to the supervisor when RH remains above the threshold after corrective action. Weekly RH trend analysis by the Section Head of Raw Materials is included as a continuous improvement mechanism.

b. Improvement 2: Enhanced Material Receiving Inspection Procedure (RPN = 336). The improvement proposes adding a physical open inspection method as a complement to the existing visual inspection. A minimum of 10% of jumbo bags per truck (approximately 3 units per 30-unit delivery) are to be physically opened and inspected for hardness and internal agglomeration signs, based on ANSI/ASQ Z1.4 acceptance sampling principles adapted to actual workforce capacity and delivery volume. Materials declared reject based on the inspection criteria, specifically hard agglomerates found on 50% or more of inspected surfaces, are quarantined separately and reported to the Section Head for supplier claim procedures.

c. Improvement 3: Stacking Height Limitation to Maximum 2 Tiers (RPN = 288). Reducing the stacking height from three tiers to a maximum of two tiers reduces the mechanical pressure on the lowest jumbo bag from approximately 2 tons to approximately 1 ton, a 50% reduction in mechanical load. All jumbo bags are to be placed on wooden or plastic pallets for uniform load distribution and to prevent direct floor contact. A minimum 50 cm spacing between stacks is required for air circulation and inspection access. When incoming delivery volumes exceed two-tier storage capacity, the Section Head of Raw Materials coordinates with the logistics team to adjust delivery scheduling.

d. Improvement 4: FIFO Stock Management System with Early Warning Mechanism (RPN = 150). A First In First Out stock management system is proposed, supported by labeling each jumbo bag with arrival date, batch number, and maximum storage limit of H+4 from arrival date. The inventory system is configured to display an early warning notification at H+3 and a critical alert at H+4, enabling supervisors to prioritize material for immediate use or coordinate with the production line before the material reaches a high-risk storage duration. Table 6 presents the consolidated summary of all improvement proposals.

Table 6. Improvement Proposals Summary by RPN Priority

No	Failure Mode (RPN)	Aspect Improved	Improvement Proposal	Target Parameter
1	High warehouse RH (448)	Storage environment humidity control	Warehouse RH Control SOP	Reduce Occurrence; Improve Detection
2	Incomplete inspection (336)	Material receiving inspection system	Enhanced Receiving Inspection Procedure	Improve Detection
3	Three-tier stacking (288)	Mechanical pressure on jumbo bags	Maximum 2-Tier Stacking Configuration	Reduce Severity and Occurrence
4	Storage duration 4 days or more (150)	Stock rotation and storage duration control	FIFO Stock Management System with Early Warning	Reduce Occurrence; Improve Detection

3.5. Control Stage

As this study focused on improvement design rather than post-implementation validation, the Control stage was developed as a proposed sustainability mechanism intended for application once the four improvement proposals are adopted by the company. The proposed mechanism comprises three integrated components.

The first component is a monitoring plan with quantitative success indicators for each improvement proposal. RH control is monitored daily with a target of at least 80% of working days per month achieving RH at or below 60% during operational hours. Receiving inspection effectiveness targets zero caked materials passing into warehouse storage per month. Stacking compliance targets at least 95% of storage cycles adhering to the two-tier maximum per month. FIFO compliance targets at least 90% of materials consumed before H+4 from arrival date. All indicators are evaluated cumulatively each month by the Section Head of Raw Materials, with the 24.15% baseline defect rate established at PT XYZ as the reference benchmark for improvement evaluation.

The second component consists of three operational control forms designed for direct field use. The Daily RH Control Form records monitoring results three times per shift with columns for RH value, status (at or below 60%, or above 60%), corrective action taken, and operator name. The Material Receiving Inspection Form documents inspection results per delivery including number of units, number of physically opened

samples, packaging condition, material hardness, agglomeration indication, and accept or reject decision. The Stock and Stacking Monitoring Form combines FIFO compliance and stacking height compliance in a single form, using a color-coded storage duration status system: Safe (at or before H+2), Caution (H+3, early warning), and Critical (H+4, requiring supervisor escalation).

The third component is a periodic internal audit schedule covering five audit aspects at different frequencies, from daily spot checks of stacking compliance to monthly defect rate reviews comparing against the 24.15% baseline. Table 7 presents the complete internal audit schedule.

Table 7. Periodic Internal Audit Schedule, Control Stage at PT XYZ

Audit Aspect	Frequency	Audit Method	Auditor	Output
RH Control SOP Compliance	Weekly	Review daily RH control forms; direct warehouse RH observation	Section Head of Raw Materials	Weekly RH trend report
Receiving Inspection Procedure Compliance	Each delivery and monthly summary	Verify receiving forms; direct inspection process observation	Warehouse Supervisor	Monthly inspection summary; reject case records
Maximum 2-Tier Stacking Compliance	Daily spot check and weekly full audit	Visual observation of storage area; photographic documentation of stacking conditions	Warehouse Supervisor	Non-conformance records; weekly compliance report
FIFO System Compliance	Daily system checks and monthly full audit	Verify date labels; cross-check inventory system against physical stock	Section Head of Raw Materials	Monthly storage duration summary; critical material alert records
Overall Caking Defect Rate	Monthly	Actual defect data recapitulation; comparison against 24.15% baseline	Section Head and Supervisor	Monthly defect trend report; overall improvement effectiveness evaluation

The proposed monitoring and control plan is designed as a feedback loop that enables management to adjust procedures based on audit findings, ensuring the storage control system can adapt continuously to changes in operational conditions.

4. Conclusion

This study aimed to analyze the occurrence of caking defects in sodium sulfate storage and to propose an improved storage control system using the Six Sigma DMAIC framework integrated with FMEA and p-chart analysis. The findings demonstrate that the storage system at PT XYZ operates at a low process capability level of approximately 2.20 sigma, with an average defect proportion of 24.15% and statistically unstable performance indicated by multiple out-of-control points, confirming that caking defects are driven by identifiable and controllable factors rather than random variation. The analysis reveals that high warehouse relative humidity is the most critical factor, followed by inadequate inspection procedures, excessive stacking height, and prolonged storage duration, where these factors interact synergistically to increase both defect occurrence and severity. The integration of DMAIC with FMEA enables systematic root cause identification and risk prioritization, ensuring that improvement efforts are directed toward the most impactful failure modes. The proposed improvement system, consisting of RH control SOP, enhanced receiving inspection, two-tier stacking configuration, and FIFO-based stock management with early warning, provides a comprehensive and integrated approach to reducing defects and improving detection capability. This study highlights the critical importance of raw material storage control in maintaining overall process quality performance, demonstrating that significant defects can originate in pre-production stages despite compliant material specifications. However, the study is limited to a single observation period and focuses on improvement design without post-implementation validation; therefore, future research is recommended to conduct longitudinal studies to evaluate improvement effectiveness, perform statistical comparison before and after implementation, and

incorporate economic analysis as well as explore automated humidity control and real-time monitoring systems for enhanced storage management.

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