Technema: Journal of Intelligent Engineering and Computing
Vol 1 No 3 September 2026, Hal 232-243
ISSN: 3163-6020 (Print) ISSN: 3163-5997 (Electronic)
Open Access: https://sovereignresearch.org/technema

Proposal for Improving the Production Process of CVT Slide Pieces Made from Pineapple Leaf Fiber Composites Using the Six Sigma Method

Aura Khanza Mutiara[1]
[1] Institut Teknologi Nasional Bandung, Indonesia
Email: *khanzaaauura@gmail.com*

Article Info :
Received:
03-08-2026
Revised:
24-08-2026
Accepted:
02-09-2026

Abstract

This study proposes improvements to the production process of CVT slide pieces made from pineapple leaf fiber-reinforced Polypropylene High Impact composites using the Six Sigma DMAIC framework. Production data from five simulation sessions covering 2,000 units were analyzed through Critical to Quality identification, a P control chart, Defects per Million Opportunities, sigma level, fishbone analysis, and 5W+1H. The results identified 353 defective units, equivalent to 17.7% of total production, with flash parting line as the dominant defect at 165 cases or 46.74%. The process remained statistically in control, with a center line of 0.177, but its capability was limited, as reflected by an average DPMO of 29,416.67 and a sigma level of 3.39. Root-cause analysis identified nine causes across machine, method, material, and man factors, mainly associated with the absence of standardized process-control documents. Six improvement documents were formulated, including machine and mold checklists, inspection procedures, material preparation standards, and parameter logs. The proposed controls are projected to reduce defects to 11.45% and increase the sigma level to 3.57. These measures provide a structured basis for sustainable manufacturing quality improvement.

Keywords: *CVT slide piece, DMAIC, pineapple leaf fiber composite, quality control, Six Sigma.*

INTRODUCTION

The rapid expansion of the motorcycle industry has increased the demand for transmission components that provide sufficient mechanical strength, dimensional stability, and production efficiency. In automatic motorcycles, the *Continuously Variable Transmission* (CVT) system consists of several interacting components, including the *slide piece*, which contributes to stabilizing the movement of the *primary pulley* during transmission operation. The development of *slide piece* components has therefore shifted from conventional material utilization toward alternative materials that can reduce dependence on synthetic resources while supporting more sustainable manufacturing practices. Within this context, pineapple leaf fiber has emerged as a promising natural reinforcement because of its mechanical characteristics and its potential for use in polymer-based engineering composites (Anand et al., 2022; Liao et al., 2025).

Pineapple leaf fiber (PALF) possesses structural characteristics that support its use as a reinforcing phase in polymer composites intended for engineering applications. Previous studies have shown that fiber length, surface treatment, fiber fraction, and reinforcement distribution significantly influence the mechanical strength, wear behavior, and morphological characteristics of PALF-based composites (Anand et al., 2022; Mansingh et al., 2022). PALF-reinforced polypropylene composites have also demonstrated considerable potential for technical applications, although their performance remains sensitive to raw material preparation, fiber dispersion, and processing consistency (Sayeed et al., 2023; Salim et al., 2025). These findings indicate that the successful application of pineapple leaf fiber composites depends not only on material properties but also on the capability of the production process to maintain stable and repeatable operating conditions.

The development of pineapple leaf fiber composite-based CVT *slide pieces* has progressed through several stages, including material characterization, mold design, injection molding simulation, and production capacity improvement. Earlier studies have demonstrated that composite characteristics, mold configuration, and injection molding parameters directly affect dimensional accuracy and the overall quality of the molded product (Rachman et al., 2022; Zaidan et al., 2023). Subsequent development resulted in a 24-cavity mold design intended to increase the production capacity of CVT *slide pieces* and move the process from laboratory-scale development toward higher-volume manufacturing (Latief et al., 2024). Despite these technical advances, the stability and capability of the actual production process have received comparatively limited attention relative to material development and mold engineering.

Quality problems become particularly important when the production process is evaluated under repeated manufacturing conditions. Five production simulation sessions conducted between January and March 2026 produced 2,000 *slide pieces*, of which 353 units, or 17.7%, were identified as defective. Six defect categories were recorded, namely *flash parting line*, *short shot*, *sink mark*, *ejector mark*, products stuck in the core, and dimensional nonconformity, with *flash parting line* accounting for 165 cases or 46.74% of all defects. This defect proportion indicates that increased production capacity has not yet been accompanied by sufficient process consistency, making systematic quality control necessary to distinguish routine process variation from causes that require corrective intervention.

One structured approach for controlling process variation and improving process capability is the Six Sigma methodology through the *Define, Measure, Analyze, Improve,* and *Control* (DMAIC) framework. DMAIC enables quality problems to be defined through *Critical to Quality* characteristics, quantitatively measured using indicators such as *Defects per Million Opportunities* (DPMO) and sigma level, analyzed to identify root causes, and translated into improvement and control actions. Applications of DMAIC in manufacturing environments have demonstrated its effectiveness in reducing defects, improving operational performance, and establishing more systematic process control mechanisms (Condé et al., 2023; Mittal et al., 2023). Its effectiveness is further strengthened by the use of statistical tools and cause-and-effect analysis, which support evidence-based decision-making rather than reliance on operator experience alone (Araman & Saleh, 2023; Yu et al., 2022).

Although the literature on PALF composites and Six Sigma has expanded considerably, these two research streams have generally developed separately. PALF studies have primarily focused on mechanical properties, surface characteristics, fiber fraction, wear resistance, and fiber–matrix compatibility (Anand et al., 2022; Sayeed et al., 2023; Liao et al., 2025), whereas Six Sigma studies have largely examined defect reduction and process improvement in conventional manufacturing systems (Condé et al., 2023; Mittal et al., 2023). In the specific context of CVT *slide pieces*, previous research has concentrated on material characterization, mold and bracket design, cavity capacity, and injection molding simulation (Rachman et al., 2022; Zaidan et al., 2023; Latief et al., 2024). Consequently, limited evidence is available on the integration of PALF composite characteristics, actual production defects, process capability measurement, dominant defect identification, and structured improvement planning within a single quality management framework.

This gap positions the present study at the process-control stage following the earlier development of material formulations and mold designs. The novelty of the study lies in the integrated application of DMAIC to the production of pineapple leaf fiber composite CVT *slide pieces* by linking actual defect distribution, process stability, DPMO, sigma level, and root-cause analysis with the formulation of practical corrective actions. Unlike studies that terminate at material characterization or injection molding parameter simulation, the present research extends the analysis to the development of process-control instruments, including standard operating procedures, checklists, parameter logs, and in-process inspection mechanisms. Such an approach is consistent with the logic of DMAIC, in which standardization and post-improvement control are essential for maintaining sustained process performance (Condé et al., 2023; Tsarouhas & Sidiropoulou, 2024).

Accordingly, this study aims to identify the dominant defects in the production of pineapple leaf fiber composite CVT *slide pieces*, evaluate process stability and capability, and determine the principal causes underlying the most significant defect. The analysis applies the Six Sigma DMAIC framework using a P control chart, CTQ analysis, DPMO, sigma level, a 5M+1E fishbone diagram, and the 5W+1H method as mutually supporting analytical tools. The findings are subsequently used to formulate improvement proposals aimed at standardizing production activities, controlling machine and mold conditions, improving material handling consistency, and strengthening operator discipline.

Academically, the study extends the application of Six Sigma to natural-fiber composite manufacturing, while practically it provides a structured basis for improving the stability, measurability, and sustainability of CVT *slide piece* production processes (Al Faritsy & Wahyunoto, 2022; Mittal et al., 2023).

RESEARCH METHODS

This study employed a descriptive quantitative approach using the Six Sigma methodology through the *Define, Measure, Analyze, Improve,* and *Control* (DMAIC) framework. The object of the study was the production process of CVT *slide pieces* manufactured from pineapple leaf fiber-reinforced *Polypropylene High Impact* (PPHI) composites using a 24-cavity injection molding machine. Primary data were collected through direct observation, interviews with production managers and operators, and production documentation obtained from five simulation sessions conducted between January and March 2026, with a total production volume of 2,000 units. The collected data included production quantity per session, defect categories, and the number of defective units identified during each production run, while secondary data were drawn from previous studies concerning pineapple leaf fiber composite characteristics, mold development, and related injection molding processes.

Data analysis followed the five sequential stages of DMAIC. In the *Define* stage, the production flow was mapped using an *Operation Process Chart* (OPC) and SIPOC diagram, while *Critical to Quality* (CTQ) characteristics were established based on the six identified defect categories; in the *Measure* stage, process stability was evaluated using a P control chart, followed by the calculation of *Defects per Million Opportunities* (DPMO) and sigma level to determine process capability. The *Analyze* stage applied a fishbone diagram based on the 5M+1E framework *Man, Method, Machine, Material, Measurement,* and *Environment* to identify the root causes of the dominant defect, whereas the *Improve* stage used the 5W+1H method to formulate corrective actions for each identified cause. Finally, the *Control* stage translated the proposed improvements into standardized process-control documents and periodic audit mechanisms intended to maintain process consistency and support continuous quality improvement.

RESULTS AND DISCUSSION

Distribution of Production Defects and Critical Quality Characteristics

The five production simulation sessions generated a total of 2,000 CVT *slide pieces*, with production volumes varying across sessions because of differences in operating duration and raw material availability. The production quantity ranged from 230 units in Session 5 to 580 units in Session 2, indicating that the process was evaluated under different batch sizes rather than under an identical production volume. A total of 353 defective products were identified, corresponding to an overall defect proportion of 17.7%, which indicates that a substantial portion of the output failed to satisfy the specified quality characteristics. This condition is relevant to the current stage of product development because increasing mold capacity and production volume does not automatically ensure consistent product conformity when process parameters and operating procedures have not been fully standardized (Latief et al., 2024; Montgomery, 2012).

The defects recorded during production were classified into six categories, namely *flash parting line*, *short shot*, *sink mark*, *ejector mark*, products stuck in the core, and dimensional nonconformity. These categories represent different manifestations of process variation associated with mold conditions, material flow, ejection performance, dimensional stability, and injection molding parameters. The classification of defects into identifiable CTQ categories is an essential step in Six Sigma analysis because each category represents a measurable opportunity for process failure that can subsequently be incorporated into DPO and DPMO calculations (Utomo et al., 2022; Pyzdek & Keller, 2018). A clearly defined defect structure also allows quality improvement activities to be directed toward the most influential sources of nonconformity rather than treating all production failures as a single undifferentiated problem.

Among the six categories, *flash parting line* was consistently the most frequent defect in all five production sessions, with 42 cases in Session 1, 36 in Session 2, 26 in Session 3, 35 in Session 4, and 26 in Session 5. The cumulative frequency reached 165 cases, representing 46.74% of the total 353 defects, making this category considerably more dominant than any other observed defect. Such recurrence across all sessions suggests that the defect is associated with a persistent characteristic of the process rather than an isolated production incident. Similar Six Sigma applications emphasize that repetitive defects occurring across multiple production cycles should be treated as systematic quality problems requiring root-cause investigation rather than temporary operator adjustment (Firmansyah & Yuliarty, 2020; Condé et al., 2023).

The second most frequent category was *short shot*, which accounted for 62 defects or 17.56% of total defects, followed by *sink mark* with 45 cases or 12.75%. *Ejector mark* contributed 38 cases or 10.76%, products stuck in the core accounted for 25 cases or 7.08%, and dimensional nonconformity contributed 18 cases or 5.10%. The wide difference between the first and subsequent categories indicates that the defect structure was highly concentrated rather than evenly distributed across the six CTQs. This pattern is important in improvement planning because process capability can often be enhanced more effectively by prioritizing the defect category with the greatest contribution before expanding corrective actions to lower-frequency defects (Montgomery, 2012; Al Faritsy & Wahyunoto, 2022).

The observed distribution also reflects the technical complexity of processing natural-fiber-reinforced polymer composites through injection molding. Pineapple leaf fiber can alter melt-flow behavior, viscosity, fiber dispersion, and the interaction between the composite and mold cavity, making process consistency particularly sensitive to material preparation and operating parameters (Anand et al., 2022; Sayeed et al., 2023). Previous studies on pineapple leaf fiber composites have similarly demonstrated that fiber characteristics, treatment, and distribution affect mechanical and morphological performance, indicating that material variability can subsequently influence molding behavior (Mansingh et al., 2022; Salim et al., 2025). The defect frequencies presented in Table 1 therefore provide not only an indication of product nonconformity but also an empirical basis for identifying where interactions among material, mold, machine, and operating method may be affecting production quality.

Table 1. Number of CVT *Slide Piece* Defects by Defect Type and Production Session

No.	Defect Type	Sesi 1	Sesi 2	Sesi 3	Sesi 4	Sesi 5	Jumlah	%
1	*Flash parting line*	42	36	26	35	26	165	46,74
2	*Short shot*	15	14	10	13	10	62	17,56
3	*Sink mark*	11	10	7	9	8	45	12,75
4	Ejector Mark	9	9	6	8	6	38	10,76
5	Stuck in Core	6	6	4	5	4	25	7,08
6	Dimensional Nonconformity	5	4	2	6	1	18	5,10
	Total	88	79	55	76	55	353	100

Source: Production simulation data, January–March 2026

The dominance of *flash parting line* is particularly important because this defect alone contributed almost half of all nonconformities generated during the production simulations. Its frequency was approximately 2.66 times that of *short shot*, which was the second largest defect category, demonstrating a clear concentration of quality losses in a single CTQ. In injection molding, flash commonly indicates that molten material has passed through an unintended opening along the mold separation surface, a condition that can be associated with clamping performance, mold wear, improper mold installation, or inappropriate processing parameters. Previous investigations of CVT *slide piece* mold design have shown that mold geometry and injection conditions are integral to the dimensional and production performance of the component, supporting the need to examine the mold–machine interaction in greater detail (Rachman et al., 2022; Latief et al., 2024).

The occurrence of *short shot* as the second largest defect category provides additional evidence that material flow remains an important issue in the current process. A *short shot* occurs when molten material fails to completely fill the mold cavity, which can be related to insufficient material volume, premature solidification, inadequate injection pressure, or restricted material flow. Observations during the production simulations indicated that the raw material volume inside the machine tended to decrease toward the end of some sessions, allowing the material to solidify before all cavities were completely filled. This finding is consistent with previous injection molding research in which inadequate cavity filling was associated with process and flow conditions, while the use of fiber-reinforced composites can further increase the sensitivity of melt flow to material preparation and processing conditions (Iskandar & Vendiza, 2019; Sayeed et al., 2023).

The presence of *sink mark*, *ejector mark*, products stuck in the core, and dimensional nonconformity further indicates that the quality problem is not attributable to a single technical mechanism. *Sink marks* may reflect localized shrinkage behavior, while ejection-related defects indicate possible inconsistencies in mold release, ejector operation, or cooling conditions. Previous studies on polymer composite molding have shown that mold temperature and processing conditions can influence shrinkage-related defects, while CVT *slide piece* development research has emphasized the importance of mold design and material characteristics in maintaining dimensional conformity (Sanjaya & Anggraeni, 2022; Zaidan et al., 2023). The simultaneous occurrence of several defect categories therefore suggests that improvement should ultimately address the production system as an interconnected process rather than focus exclusively on final-product inspection.

From a Six Sigma perspective, the distribution in Table 1 provides a quantitative basis for determining improvement priorities before proceeding to process capability and root-cause analysis. The substantial difference between *flash parting line* and the remaining defect categories is consistent with the logic of prioritizing the “vital few” quality problems that account for a disproportionate share of total process losses. DMAIC-based manufacturing studies have demonstrated that identifying and prioritizing dominant defect categories during the *Define* and *Measure* stages enables subsequent analytical resources to be concentrated on the sources with the greatest potential impact on overall process performance (Mittal et al., 2023; Yu et al., 2022). Accordingly, selecting *flash parting line* as the primary defect for detailed analysis is supported by the observed frequency distribution rather than by subjective judgment.

The results also demonstrate that product quality cannot be evaluated solely from the successful production of 2,000 units because production quantity and process capability represent fundamentally different performance dimensions. Although the multi-cavity mold supports higher throughput, the 17.7% overall defect proportion indicates that production expansion has introduced or preserved quality losses that must be addressed before the process can be regarded as technically mature. The objective of Six Sigma is therefore not merely to increase output but to reduce process variation and defect opportunities through measured and controlled operational improvements (Pyzdek & Keller, 2018; Condé et al., 2023). This distinction is particularly relevant for a developing product such as a natural-fiber composite CVT *slide piece*, where production scalability should be accompanied by repeatability and conformance.

Overall, the defect distribution confirms that the current CVT *slide piece* production process exhibits a structured pattern of nonconformity dominated by *flash parting line*. The 165 occurrences of this defect, representing 46.74% of total defects, provide a strong empirical justification for placing it at the center of the subsequent DMAIC analysis, while the remaining defect categories remain relevant as secondary quality concerns. The findings also reinforce the need to connect material characteristics, mold conditions, machine parameters, and operating practices when evaluating the production of pineapple leaf fiber composite components, as emphasized in both natural-fiber composite and manufacturing quality literature (Anand et al., 2022; Latief et al., 2024; Mittal et al., 2023). The next analytical stage therefore requires an assessment of whether the observed defect proportions remain statistically stable across production sessions and how the resulting process performance is reflected in DPMO and sigma-level measures.

Statistical Process Stability and Six Sigma Capability

The stability of the CVT *slide piece* production process was evaluated using a P control chart because the number of units produced differed across the five simulation sessions. The overall center line (CL) was 0.177, representing the average proportion of defective units generated throughout the production period. All observed defect proportions remained within their respective upper control limits (UCL) and lower control limits (LCL), indicating that no production session exhibited a statistically detectable *special cause* variation. This pattern suggests that the process was statistically stable, although statistical stability should not be interpreted as evidence that the resulting quality level was operationally satisfactory (Montgomery, 2012; Pyzdek & Keller, 2018).

The width of the control limits varied among production sessions because the sample size differed for each batch. Sessions with smaller production quantities generated wider control intervals, whereas sessions with larger batch sizes produced narrower intervals because the standard error of the defect proportion decreases as the subgroup size increases. Session 5, with 230 units, had an LCL of 0.101 and a UCL of 0.252, resulting in a wider control range than Session 2, which produced 580 units and had a range of 0.129–0.224. This statistical characteristic confirms the importance of using a P chart rather than an *np* chart when subgroup sizes are unequal, as recommended in statistical quality-control applications (Montgomery, 2012; Al Faritsy & Wahyunoto, 2022).

Table 2. P Control Chart Calculation for Each Production Session

Session	Production Quantity	Number of Defects	Defect Proportion (P)	CL	LCL	UCL	Process Status
Session 1	420	88	0.210	0.177	0.121	0.232	In Control
Session 2	580	79	0.136	0.177	0.129	0.224	In Control
Session 3	260	55	0.212	0.177	0.106	0.247	In Control
Session 4	510	76	0.149	0.177	0.126	0.227	In Control
Session 5	230	55	0.239	0.177	0.101	0.252	In Control

Session 5 deserves particular attention because it generated the highest observed defect proportion, with P = 0.239, while simultaneously approaching its UCL of 0.252. The difference of only 0.013 between the observed proportion and the upper control boundary indicates that the session remained statistically controlled but operated close to the threshold at which a special cause could become detectable. This condition suggests that even a relatively small deterioration in material flow, mold condition, machine setting, or operator practice could shift the process beyond the statistical control limit. In practical manufacturing environments, such borderline observations should therefore be treated as early warnings for preventive intervention rather than interpreted solely as acceptable observations because they remain inside formal limits (Pyzdek & Keller, 2018; Firmansyah & Yuliarty, 2020).

The statistical stability observed across the five sessions indicates that the defect pattern was primarily attributable to *common cause variation* embedded in the existing production system. This finding is more consequential than an isolated abnormal event because it implies that the current process repeatedly produces a relatively high level of nonconformity under its normal operating conditions. The overall defect proportion of 17.7% therefore reflects a systemic production problem rather than a short-term deviation that could be corrected only by adjusting a single operating cycle. Previous DMAIC studies similarly emphasize that stable but incapable processes require structural improvement of process methods, equipment conditions, and operating standards rather than temporary corrective actions (Condé et al., 2023; Araman & Saleh, 2023).

Statistical stability was subsequently complemented by a Six Sigma capability assessment using *Defects per Opportunity* (DPO), *Defects per Million Opportunities* (DPMO), and sigma level. Six CTQs were used as the number of potential defect opportunities for each produced unit, corresponding to the six defect categories identified during the *Define* stage. This measurement converts observed defects into a standardized metric that enables performance comparisons across sessions with different production quantities. The results show substantial variation in process capability despite the absence of observations outside the control limits, demonstrating that a statistically controlled process may still perform at an inadequate quality level (Yu et al., 2022; Mittal et al., 2023).

Table 3. DPMO and Sigma Level by Production Session

Session	Production Quantity	Number of Defects	CTQ	DPO	DPMO	*Sigma Level*
Session 1	420	88	6	0.03492	34,920	3.31
Session 2	580	79	6	0.02270	22,701	3.51
Session 3	260	55	6	0.03526	35,256	3.31
Session 4	510	76	6	0.02484	24,837	3.46
Session 5	230	55	6	0.03986	39,855	3.25
Average	**2,000**	**353**	**6**	**0.02942**	**29,416.67**	**3.39**

Session 2 achieved the best capability performance, with a DPMO of 22,701 and a sigma level of 3.51, while Session 5 recorded the weakest performance, with 39,855 DPMO and a sigma level of 3.25. Session 4 occupied an intermediate position with 24,837 DPMO and a sigma level of 3.46, whereas Sessions 1 and 3 displayed nearly identical capability levels of 3.31. The difference between the best and worst session was therefore 0.26 sigma, indicating that production quality was not fully consistent across operating sessions even though all observations remained statistically controlled. Such variability supports the need for standardized machine settings, material preparation, mold inspection, and operator procedures to reduce performance differences between batches (Mittal et al., 2023; Tsarouhas & Sidiropoulou, 2024).

The average DPMO of 29,416.67 indicates that approximately 29,417 defects would theoretically occur for every one million opportunities if the observed process performance were maintained. This performance lies between the conventional three-sigma and four-sigma capability levels and remains substantially above the ideal Six Sigma benchmark of approximately 3.4 defects per million opportunities. The corresponding average sigma level of 3.39 therefore characterizes the production system as functioning at a moderate capability level but still far from a highly capable process. The result confirms that statistical control and process capability must be evaluated separately because a process can exhibit predictable variation while continuing to generate an economically and technically undesirable number of defects (Montgomery, 2012; Pyzdek & Keller, 2014).

The relatively weak process capability is also consistent with the developmental status of the production system, which has not yet reached full routine manufacturing conditions. The production process currently relies on limited historical data, several simulation sessions, and operating practices that remain dependent on individual experience rather than fully documented standards. Six Sigma applications in manufacturing have shown that the absence of standardized procedures often produces persistent variation in machine setup, inspection practices, and operator decision-making, thereby limiting capability improvement even when the process remains statistically stable (Araman & Saleh, 2023; Condé et al., 2023). The present findings therefore indicate that improving the process requires not only technical adjustment of injection parameters but also stronger procedural control over how the process is executed and documented.

The use of pineapple leaf fiber reinforcement introduces an additional source of production sensitivity because natural fibers can affect melt flow, viscosity, dispersion, and filling behavior during polymer processing. Studies of PALF-reinforced composites have demonstrated that mechanical performance is strongly influenced by fiber length, surface condition, volume fraction, and distribution within the polymer matrix (Anand et al., 2022; Mansingh et al., 2022). Similar findings for polypropylene-based natural fiber composites indicate that variations in fiber morphology and composite preparation can influence both final material properties and manufacturing consistency (Sayeed et al., 2023; Salim et al., 2025). Consequently, the measured DPMO and sigma level should be interpreted as the combined outcome of machine, mold, material, method, and operator-related variability rather than as an isolated indicator of injection molding machine performance.

The consistency between the P-chart results and the capability analysis provides a coherent interpretation of the current production condition. The process is statistically controlled because no session exceeds its control limits, yet it remains insufficiently capable because the average DPMO is 29,416.67 and the sigma level is only 3.39. This combination indicates that the existing defect level has become an inherent part of the production system and therefore requires systematic changes to the process rather than isolated troubleshooting activities. Such a condition corresponds closely with the DMAIC logic in which the *Measure* stage establishes the quantitative baseline required before the *Analyze* stage identifies the dominant sources of process failure (Yu et al., 2022; Mittal et al., 2023).

Overall, the measurement results demonstrate that the production system has achieved repeatability in a statistical sense but has not yet achieved the capability required for reliable high-quality manufacturing. The relatively poor performance of Session 5 and the persistent average defect level indicate that process standardization should be prioritized before production capacity is expanded further. These findings also strengthen the decision to focus subsequent root-cause analysis on *flash parting line*, which accounted for 46.74% of all recorded defects and therefore represents the largest single opportunity for reducing the overall DPMO. The following subsection accordingly examines the causal structure of this dominant defect and translates the identified causes into process-improvement and control measures within the *Analyze, Improve,* and *Control* stages of DMAIC.

Root-Cause Analysis, Improvement Proposals, and Process Control

The *Analyze* stage focused on *flash parting line* because this defect contributed 165 cases, or 46.74% of all defects identified during the five production sessions. Root-cause identification using the 5M+1E fishbone framework generated nine causes distributed across four categories, namely *machine, method, material,* and *man*, whereas no relevant causal factors were identified under *measurement* and *environment* based on field observations. This concentration indicates that the dominant quality problem originated primarily from technical equipment conditions, production procedures, composite-material handling, and operator practices rather than from external environmental variation. The use of structured cause-and-effect analysis is consistent with Six Sigma applications in which dominant defects are decomposed into controllable causal factors before improvement actions are formulated (Pratiwi et al., 2026; Pyzdek & Keller, 2018).

Two causes were identified under the *machine* factor, namely declining clamping force and wear along the mold parting surface. Reduced clamping force on the Bole 170 EKH injection molding machine can decrease the ability of the mold to resist the internal pressure generated by molten composite during injection, allowing material to escape through the parting line and form flash. Repeated mold use can simultaneously produce microscopic wear along the closing surface, thereby creating additional pathways through which molten material can overflow during injection. These findings are technically consistent with injection molding principles that identify mold closure accuracy, clamping capacity, cavity condition, and injection pressure as critical determinants of flash formation and molded-product conformity (Rosato et al., 2000; Latief et al., 2021).

The *method* factor contained three causes: imprecise mold installation, the absence of mold cleaning during production, and instability in injection parameters involving pressure, temperature, and injection time. All three conditions were linked to the absence of formal standard operating procedures, resulting in production decisions being based largely on individual routines rather than documented operating standards. Such dependence on operator judgment can produce differences in machine setting, mold preparation, and inspection frequency even when the same equipment and material formulation are used. This finding supports the broader quality-management principle that process consistency requires documented procedures, standardized operating criteria, and repeatable work sequences rather than reliance solely on experiential knowledge (Mutaufiq, 2021; Simbolon, 2020; Condé et al., 2023).

Two additional causes were identified under the *material* factor, namely fiber agglomeration within the PPHI matrix and nonuniform pineapple leaf fiber size after sieving. Fiber agglomeration can restrict melt flow and disturb pressure distribution inside the cavity, while variation in fiber size may reduce mixture homogeneity and cause inconsistent rheological behavior during injection. These conditions are particularly important in natural-fiber composites because PALF characteristics, fiber fraction, morphology, dispersion, and preparation can substantially affect composite behavior and processability (Anand et al., 2022; Sayeed et al., 2023; Liao et al., 2025). The finding is also consistent with previous studies on pineapple-fiber composite development indicating that material composition and fiber characteristics influence mechanical performance and production quality, thereby requiring tighter control during preparation and mixing (Prianto, 2023; Boangmanalu et al., 2025).

The *man* factor comprised the absence of routine mold inspection by operators before production and variation in machine-setting practices among operators. These causes indicate that procedural weaknesses were translated directly into behavioral variation because operators had no formal checklist or parameter record against which machine and mold readiness could be verified. Previous Six Sigma applications demonstrate that standardized documentation is necessary to reduce individual variation and convert tacit operational knowledge into repeatable process controls, especially in developing manufacturing systems (Sinatra et al., 2017; Mittal et al., 2023). Taken together, the nine root causes indicate that the dominant defect was not generated by a single isolated failure but by interactions among machine condition, work methods, material preparation, and operator behavior.

The synthesis of the root-cause analysis showed that the nine causes converged on a common systemic weakness: the absence of formal process-control documentation. The *Improve* stage therefore did not formulate nine separate corrective measures but consolidated related causes into six control documents designed to address multiple causal pathways simultaneously. This approach follows the logic of DMAIC, in which improvement actions should be traceable to verified causes while remaining feasible for routine implementation and subsequent control (Antony et al., 2012; Araman & Saleh, 2023). The resulting relationship between root causes and the proposed implementation documents is presented in Table 4 without altering the underlying production findings.

Table 4. Summary of Improvement Proposals and Implementation Documents

No.	Root Cause	Factor	Document Form
1	No machine checklist before production	*Machine*	Machine Condition Checklist
2	No mold checklist before production	*Machine*	Mold Inspection Checklist
3	No mold inspection SOP available	*Method*	Mold Inspection SOP
4	No in-process inspection SOP available	*Method*	Production Process Inspection SOP
5	No injection process SOP available	*Method*	Machine Condition Checklist (integrated)
6	No material mixing SOP	*Material*	Material Mixing and Sieving SOP
7	No material sieving SOP	*Material*	Material Mixing and Sieving SOP
8	No operator parameter sheet	*Man*	Parameter Log
9	No work instruction for mold inspection	*Man*	Mold Inspection Checklist (integrated)

The consolidation shown in Table 4 reflects functional overlap among several causes and avoids unnecessary duplication of operational documents. For example, the Mold Inspection Checklist simultaneously addresses undetected parting-line wear and the absence of mandatory operator inspection before production, while the Material Mixing and Sieving SOP addresses both fiber agglomeration and variation in fiber size. The mold checklist includes visual inspection of the parting surface, cavity and core cleanliness, ejector-pin operation, bolt and locking condition, and cooling-channel condition, each accompanied by acceptance criteria and corrective actions. This form of integrated control is consistent with previous CVT *slide piece* mold-development studies showing that mold design, mold condition, and process preparation must function as a coordinated system rather than as isolated engineering elements (Rachman et al., 2022; Latief et al., 2024).

The proposed documents were arranged according to the actual sequence of production activities so that control is embedded throughout the process rather than concentrated at final inspection. The Machine Condition Checklist and Mold Inspection Checklist are completed before production, followed by the Mold Inspection SOP and the Material Mixing and Sieving SOP during preparation, while the Production Process Inspection SOP introduces additional checks before the composite enters the hopper and after the first three to five molding cycles. The Parameter Log records machine parameters at the beginning, middle, and end of each production session together with production data and operator evaluation notes, thereby improving traceability across batches. This shift from *end-of-line* inspection toward *in-process* control is consistent with modern quality improvement practices that emphasize defect prevention and early detection rather than corrective sorting after production has been completed (Al Faritsy & Wahyunoto, 2022; Yu et al., 2022).

The *Control* stage was designed to ensure that the proposed documents function as active process-control instruments rather than administrative records. Two mechanisms were established: formal implementation and periodic review of SOPs, and monthly production audits covering SOP compliance, physical mold condition, injection molding machine calibration, and the consistency between defect records and actual product conditions. Periodic review was proposed every three months or earlier when a new defect pattern emerges, while digital and printed copies of the procedures are maintained to facilitate operator access. Such institutionalization of corrective actions is fundamental to Six Sigma because improvements that are not supported by monitoring, documentation, and accountability can deteriorate after the initial intervention period (Pyzdek & Keller, 2014; Tsarouhas & Sidiropoulou, 2024).

The potential effect of the proposed controls was estimated through expert judgment with the production team by assuming that disciplined implementation could prevent at least 75% of potential *flash parting line* defects. Under this assumption, 124 of the existing 165 flash defects would be eliminated, reducing the projected total number of defects from 353 to 229 units, the overall defect proportion from 17.7% to 11.45%, and DPMO from 29,416.67 to 19,083, while increasing the sigma level from 3.39 to 3.57. These figures represent a projected improvement target rather than empirical post-implementation evidence and should therefore be validated through subsequent documented production trials. Nevertheless, the projected direction of improvement is consistent with empirical Six Sigma studies showing that structured DMAIC interventions can reduce manufacturing defects and improve measurable process capability when corrective actions are linked to verified root causes (Firmansyah & Yuliarty, 2020; Mittal et al., 2023).

Overall, the third stage of the analysis demonstrates that the dominant quality problem is rooted less in the technical feasibility of pineapple leaf fiber composites than in the absence of systematic process standardization surrounding their manufacture. Previous material and mold studies have established the technical basis for PALF-reinforced components and CVT *slide piece* production, but the present findings show that product commercialization also requires stable operational routines, documented inspection, controlled machine parameters, and consistent material preparation (Zaidan et al., 2023; Salim et al., 2025). Initial operator verification indicated that the proposed documents could transform machine and mold inspection from informal practices into structured activities, standardize previously subjective material preparation, and shift defect detection from final inspection toward early process monitoring, although this assessment remains qualitative until post-implementation production data are collected. The combined *Analyze–Improve–Control* results therefore support the application of Six Sigma as an integrated framework for moving the PALF composite CVT *slide piece* from developmental production toward a more stable, measurable, and continuously controlled manufacturing process.

CONCLUSION

The study demonstrates that the production process of pineapple leaf fiber composite CVT *slide pieces* remains statistically controlled but has not yet achieved adequate process capability. Among 2,000 units produced across five simulation sessions, 353 defective units were identified, corresponding to a total defect proportion of 17.7%, with *flash parting line* representing the dominant defect at 165 cases or 46.74% of all defects. The P control chart showed that all production sessions remained within the control limits, with a center line of 0.177, indicating that the observed variation was predominantly attributable to common causes. However, the average DPMO of 29,416.67 and sigma level of 3.39 indicate that the production process still requires systematic quality improvement before higher-volume manufacturing can be implemented reliably.

Root-cause analysis identified nine causes distributed across the *machine, method, material,* and *man* factors, with the absence of standardized process-control documentation emerging as the principal systemic weakness. Six improvement instruments were therefore proposed, consisting of machine and mold inspection checklists, mold inspection procedures, in-process inspection procedures, material mixing and sieving standards, and parameter logs, supported by periodic reviews and monthly production audits. The proposed controls are projected to reduce the total defect proportion from 17.7% to 11.45%, decrease DPMO from 29,416.67 to 19,083, and improve the sigma level from 3.39 to 3.57. These findings provide a practical basis for establishing a more standardized, measurable, and sustainable quality-control system for pineapple leaf fiber composite CVT *slide piece* production.

REFERENCES

Al Faritsy, A. Z., & Wahyunoto, A. S. (2022). Analisis pengendalian kualitas produk meja menggunakan metode Six Sigma pada PT XYZ. *Jurnal Rekayasa Industri, 4*(2), 52–62. https://doi.org/10.37631/jri.v4i2.707

Anand, P. B., Lakshmikanthan, A., Chandrashekarappa, M. P. G., Selvan, C. P., Pimenov, D. Y., & Giasin, K. (2022). Experimental investigation of effect of fiber length on mechanical, wear, and morphological behavior of silane-treated pineapple leaf fiber reinforced polymer composites. *Fibers, 10*(7), 56. https://doi.org/10.3390/fib10070056

Antony, J., Krishan, N., Cullen, D., & Kumar, M. (2012). Lean Six Sigma for higher education institutions (HEIs): Challenges, barriers, success factors, tools/techniques. *International Journal of Productivity and Performance Management, 61*(8), 940–948. https://doi.org/10.1108/17410401211277165

Araman, H., & Saleh, Y. (2023). A case study on implementing Lean Six Sigma: DMAIC methodology in aluminum profiles extrusion process. *The TQM Journal, 35*(2), 337–365. https://doi.org/10.1108/TQM-05-2021-0154

Boangmanalu, E. P. D., Saragi, J. F. H. T., Pratama, A. B., Sahat, S., & Bangun, P. (2025). Uji kekuatan tarik komposit epoksi diperkuat serat daun nanas (*Ananas comosus*) berdasarkan variasi fraksi volume serat. *Jurnal INOVATOR, 8*(2), 123–128. https://doi.org/10.37338/inovator.v8i2.507

Condé, G. C. P., Oprime, P. C., Pimenta, M. L., Sordan, J. E., & Bueno, C. R. (2023). Defect reduction using DMAIC and Lean Six Sigma: A case study in a manufacturing car parts supplier. *International Journal of Quality & Reliability Management, 40*(9), 2184–2204. https://doi.org/10.1108/IJQRM-05-2022-0157

Firmansyah, R., & Yuliarty, P. (2020). Implementasi metode DMAIC pada pengendalian kualitas sole plate di PT Kencana Gemilang. *Jurnal PASTI (Penelitian dan Aplikasi Sistem dan Teknik Industri), 14*(2), 167–180. https://doi.org/10.22441/pasti.2020.v14i2.007

Iskandar, N., & Vendiza, F. R. (2019). Analisis cacat short shot dalam proses injection molding pada komponen shroud fan. *Prosiding Seminar Nasional Sains dan Teknologi, 1*(1), 101–106. https://doi.org/10.36499/psnst.v1i1.2829

Latief, A. E., Darusman, L., Fahla, W. P., Zaidan, A. D., & Anggraeni, N. D. (2021). Perancangan cetakan injection molding hand press untuk produk slide piece CVT menggunakan FEM. *METAL: Jurnal Sistem Mekanik dan Termal, 5*(2), 105–113. https://doi.org/10.25077/metal.5.2.105-113.2021

Latief, A. E., Sirodz, M. P. N., Saefudin, A. P., Prianto, R., Sarmada, S., & Irfan, L. M. (2024). Designing CVT slide piece molds for cavity 24 pieces on injection molding machine. *METAL: Jurnal Sistem Mekanik dan Termal, 8*(2), 56–62. https://doi.org/10.25077/metal.8.2.56-62.2024

Liao, S., Chen, J., & Wang, X. (2025). An update on pineapple leaf fibers. *Journal of Natural Fibers, 22*(1), Article 2509129. https://doi.org/10.1080/15440478.2025.2509129

Mansingh, B. B., Binoj, J. S., Tan, Z. Q., Eugene, W. W. L., Amornsakchai, T., Hassan, S. A., & Goh, K. L. (2022). Comprehensive characterization of raw and treated pineapple leaf fiber/polylactic acid green composites manufactured by 3D printing technique. *Polymer Composites, 43*(9), 6051–6061. https://doi.org/10.1002/pc.26906

Mittal, A., Gupta, P., Kumar, V., Al Owad, A., Mahlawat, S., & Singh, S. (2023). The performance improvement analysis using Six Sigma DMAIC methodology: A case study on Indian manufacturing company. *Heliyon, 9*(3), e14625. https://doi.org/10.1016/j.heliyon.2023.e14625

Montgomery, D. C. (2012). *Introduction to statistical quality control* (7th ed.). John Wiley & Sons.

Mutaufiq, S. (2021). *Konsep kualitas mutu*.

Pratiwi, E., Feblidiyanti, N., & Nurselvi. (2026). Analisis dan perumusan strategi peningkatan kinerja keselamatan dan kesehatan kerja menggunakan EHS pyramid index dan fishbone diagram. *Jurnal Teknologi dan Manajemen Industri Terapan, 5*(1), 355–362. https://doi.org/10.55826/jtmit.v5i1.1589

Prianto, R. (2023). *Pembuatan dan pengujian cetakan slide piece CVT untuk kapasitas 2.468 pcs per jam* Institut Teknologi Nasional Bandung..

Pyzdek, T., & Keller, P. A. (2014). *The Six Sigma handbook* (4th ed.). McGraw-Hill Education.

Pyzdek, T., & Keller, P. A. (2018). *The Six Sigma handbook* (5th ed.). McGraw-Hill Education.

Rachman, M. K., Latief, A. E., Raihan, N. M., & Dharma, S. B. (2022). Perancangan bracket cetakan dan simulasi injection molding untuk komponen slide piece CVT. *Jurnal Rekayasa Energi dan Mekanika, 2*(1), 74–82. https://doi.org/10.26760/JREM.v2i1.74

Rosato, D. V., Rosato, D. V., & Rosato, M. G. (Eds.). (2000). *Injection molding handbook* (3rd ed.). Kluwer Academic Publishers. https://doi.org/10.1007/978-1-4615-4597-2

Salim, N., Johari, F. N., Roslan, R., Abu Bakar, N. H., Abu Samah, N., Kabeb, S. M., & Sarmin, S. N. (2025). Properties of pineapple leaf fiber (PALF) reinforced polypropylene (PP) composites. *Macromolecular Symposia, 414*(1), Article 2300234. https://doi.org/10.1002/masy.202300234

Sanjaya, H., & Anggraeni, N. D. (2022). Pengaruh temperatur cetakan komposit matriks Polypropylene High Impact (PPHI) berpenguat serat nanas terhadap cacat shringkage dan sink mark menggunakan SolidWorks 2017. *e-Proceeding FTI, 1*(1).

Sayeed, M. M. A., Sayem, A. S. M., Haider, J., Akter, S., Habib, M. M., Rahman, H., & Shahinur, S. (2023). Assessing mechanical properties of jute, kenaf, and pineapple leaf fiber-reinforced polypropylene composites: Experiment and modelling. *Polymers, 15*(4), 830. https://doi.org/10.3390/polym15040830

Simbolon, S. (2020). *Kualitas mutu produk terhadap perusahaan manufaktur*.

Sinatra, O. B., Narto, N., & Lukmandono, L. (2017). Implementasi Six Sigma sebagai upaya untuk meningkatan produktivitas. *Prosiding Seminar Nasional Sains dan Teknologi, 1*(1), 111–116. https://doi.org/10.36499/psnst.v1i1.1857

Tsarouhas, P., & Sidiropoulou, N. (2024). Application of Six Sigma methodology using DMAIC approach for a packaging olives production system: A case study. *International Journal of Lean Six Sigma, 15*(2), 247–273. https://doi.org/10.1108/IJLSS-06-2022-0140

Utomo, Y., Jumali, M. A., & Salsabila, D. N. (2022). Analisis critical to quality (CTQ) pada percetakan koran di PT Temprina Media Grafika (Jawa Pos Group). *WAKTU: Jurnal Teknik UNIPA, 20*(2), 103–109. https://doi.org/10.36456/waktu.v20i02.5876

Yu, C.-M., Huang, T.-H., Chen, K.-S., & Huang, T.-Y. (2022). Construct Six Sigma DMAIC improvement model for manufacturing process quality of multi-characteristic products. *Mathematics, 10*(5), 814. https://doi.org/10.3390/math10050814

Zaidan, A. D., Latief, A. E., & Anggraeni, N. D. (2023). Analisa karakterisasi material produk slide piece CVT berbahan komposit berpenguat serat nanas dengan fraksi volume 10%. *Jurnal Rekayasa Energi dan Mekanika, 3*(1), 77–85. https://doi.org/10.26760/JREM.v3i1.77