

Need for Quality Assurance (QA) and Quality-Centric Approaches for Sustainable Growth of Indian Foundries

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Abstract – By providing cast components to the automobile, aerospace, railroad, construction, defense, and heavy engineering industries, the Indian foundry sector is essential to the manufacturing sector. Casting flaws, process unpredictability, material waste, high rejection rates, energy inefficiency, and growing international competitiveness are some of the industry's major obstacles. In this regard, sustainable industrial growth now depends on quality assurance and quality-centric methods. The necessity of methodical quality assurance procedures, process control systems, and continuous improvement techniques in Indian foundries is examined in this study. The study highlights that quality-driven systems enhance customer satisfaction and product dependability while simultaneously lowering costs and promoting long-term competitiveness and environmental sustainability. The combination of Industry 4.0, automation, and statistical quality tools for stable growth is further supported by recent research on KPI-driven foundry quality systems and sustainable control models.

Keywords – Indian foundry industry, Process quality, Quality assurance, Quality control, Six Sigma, Sustainable growth

I. INTRODUCTION

The foundry industry is one of the backbone sectors of Indian manufacturing and contributes significantly to GDP, employment, and export earnings. Foundries convert raw metals into useful cast products through processes such as molding, melting, pouring, solidification, and finishing. Since these products are used in critical industrial applications, maintaining high standards of product quality and process consistency is essential. In recent years, Indian foundries have faced growing pressure from international markets to meet stringent quality standards, reduce lead times, and adopt sustainable manufacturing practices. Traditional inspection-based approaches are no longer sufficient. Modern industries require integrated quality assurance systems that prevent defects rather than merely detect them after production. Studies show that effective quality assurance reduces scrap, rework, and customer complaints while improving productivity and profitability.

One of the oldest and most important areas of the manufacturing economy, the foundry sector provides essential support for a variety of industrial and engineering applications. Through procedures including molding, melting, pouring, solidification, fettling, and finishing, it is mostly involved in the manufacturing of metal castings. Critical industries including automotive, aircraft, railroads, construction, defense, heavy machinery, agriculture, and energy systems heavily rely on these cast components. Because of its close ties to key industrial sectors and its role

in industrial development, job creation, and export expansion, the foundry sector in India holds a critical place in the manufacturing ecosystem. India has become a major global supplier of both ferrous and non-ferrous components and is acknowledged as one of the world's top producers of castings.

Numerous small-scale, medium-sized, and structured foundry units are dispersed throughout significant industrial clusters including Karnataka, Tamil Nadu, Maharashtra, Gujarat, and West Bengal. These foundries supply components that must adhere to strict dimensional, mechanical, and metallurgical criteria for both home and foreign markets. The need for high-precision, cost-effective, and flawless castings has increased dramatically due to growing globalization and competition. The Indian foundry industry still faces a number of operational and quality-related difficulties despite its industrial significance. High rejection rates, process variability, metal waste, dimensional errors, poor surface polish, porosity defects, shrinkage cavities, and uneven mechanical qualities are common problems. These flaws have an impact on customer satisfaction and market competitiveness in addition to raising manufacturing costs through rework and scrap. Inadequate process control, a lack of established procedures, obsolete equipment, inadequate training, and a restricted use of scientific quality management techniques are frequently the underlying causes of these issues.

Quality is now a critical component of survival and long-term growth in the current competitive manufacturing environment. Consumers, particularly multinational original equipment manufacturers (OEMs), want products that meet industry-specific quality standards as well as international standards like ISO 9001 and ISO 14001. For foundry companies to sustain market relevance and long-term profitability, the implementation of quality assurance systems and quality-centric management practices is no longer optional. In the foundry industry, QA refers to a methodical framework of planned and preventive actions intended to guarantee that products continuously satisfy established standards and client expectations.

Quality assurance places more emphasis on defect prevention through process standardization, continuous monitoring, root-cause analysis, and corrective action procedures than traditional inspection-based quality control, which is primarily concerned with defect discovery after production. Reducing variability, enhancing process capabilities, and guaranteeing product reliability are all made possible by this proactive approach. Modern quality-centric approaches like Total Quality Management (TQM), Six Sigma, Lean Manufacturing, Statistical Quality Control (SQC), and Industry 4.0-based smart monitoring systems are being embraced in manufacturing sectors across the globe in addition to traditional quality assurance techniques.

These approaches emphasize staff involvement, data-driven decision-making, continuous improvement, waste reduction, and customer-focused production methods. Integrating such strategies can greatly increase operational effectiveness, lower costs, and promote sustainable industrial growth for Indian foundries.

Another crucial factor in the foundry industry is sustainability. Sustainable growth encompasses social welfare and environmental responsibility in addition to financial prosperity. By decreasing material waste, cutting energy use, lowering emissions, increasing worker safety, and boosting resource utilization, quality-centric techniques directly support sustainability. Therefore, the convergence of sustainable manufacturing and quality assurance offers a viable route for the modernization and international growth of Indian foundry businesses. The need for quality assurance and quality-centric methods in the Indian foundry industry is the main emphasis of this study, which also looks at how these methods can promote long-term industrial excellence, competitiveness, and sustainable growth.

II. LITERATURE SURVEY

Research on quality assurance, defect reduction, process optimization, and sustainable manufacturing techniques has been conducted extensively in the foundry industry. Quality control is crucial in lowering scrap, rework, and rejection rates in the metal casting industries, according to several studies. In order to increase casting quality and manufacturing efficiency, early studies emphasized the significance of systematic inspection, defect analysis, and process standardization [1]. Six Sigma and Taguchi-based techniques have been popular for process optimization and defect minimization in foundry operations as statistical quality methodologies have advanced [2], [4], [5].

According to these research, statistical methods like DMAIC frameworks, process capability analysis, and experiment design aid in lowering variability and enhancing overall product reliability. Common casting flaws include porosity, shrinkage, cold closes, inclusions, and surface blemishes were the subject of numerous investigations. Researchers found that poor control of process factors such pouring temperature, mold design, sand characteristics, and gating system layout frequently results in these errors [3], [9], [12]. Pareto charts, fishbone diagrams, control charts, and root-cause analysis are examples of quality improvement tools that have been shown to be successful in locating significant defect causes and putting corrective measures in place [10], [14], and [15]. To enhance decision-making and long-term operational performance in foundries, process knowledge management and sustainable manufacturing techniques have also been implemented [13].

Numerous scholars have examined the application of Lean Six Sigma and Six Sigma techniques in the Indian foundry sector, especially in small and medium-sized businesses. These research showed that quality-centric approaches greatly increase customer satisfaction, lower defect percentages, and boost productivity [6, 7, 8, 11]. Promising outcomes in waste reduction, lead time improvement, and process stabilization have also been demonstrated by the combination of Lean principles with Six Sigma [8]. The implementation of standardized quality frameworks for the long-term expansion of the Indian foundry industry is highly supported by these findings.

Intelligent and Industry 4.0-based quality assurance systems have been the focus of recent research. Predictive quality control and automated defect identification are increasingly utilizing artificial intelligence, deep learning, real-time process monitoring, and reinforcement learning-based defect mitigation strategies [16]–[18]. These cutting-edge methods assist smart foundry systems and allow proactive fault prevention. Additionally, quality assurance, key performance indicators (KPIs), resource optimization, and long-term industrial sustainability are directly related, according to new sustainability-focused research [20], [21]. Therefore, it is evident from the literature that quality-centric techniques are crucial for maintaining the sustained growth and global competitiveness of Indian foundry

industries, in addition to improving productivity and reducing defects.

Numerous studies have emphasized the strategic significance of combining quality assurance with sustainability and competitiveness in the foundry industry, in addition to process-oriented quality improvement. Researchers have found that quality-centric production greatly reduces costs, increases energy efficiency, and conserves resources in addition to improving the mechanical qualities and dimensional accuracy of cast components [1], [13], and [21]. According to reports, attaining zero-defect manufacturing requires the implementation of standard operating procedures, supplier quality management, personnel skill development, and preventative maintenance techniques [14], [19].

Indian foundries must adhere to international quality standards and continuous improvement procedures due to the growing demand for high-precision castings in heavy engineering, automotive, and aerospace applications [6], [7]. By cutting waste, lowering process variation, and enhancing operational transparency, digital quality monitoring systems, sensor-based inspection, and KPI-driven performance evaluation can further support sustainable manufacturing, according to recent research [17], [18], and [21]. For the long-term development of Indian foundry industries, the literature thus strongly supports the necessity of an integrated quality assurance framework that blends traditional quality instruments with cutting-edge digital and sustainability-oriented techniques.

III. NEED FOR QUALITY ASSURANCE IN INDIAN FOUNDRY INDUSTRIES

1. Reduction of Casting Defects

Product performance is negatively impacted by common foundry flaws such as blowholes, shrinkage cavities, mis-runs, cold shuts, and inclusions. Identification of the underlying reasons of sand characteristics, pouring temperature, gating design, and solidification control is aided by quality assurance. Defect rates can be greatly reduced by putting systematic inspection and process monitoring into place. Statistical quality control and defect analysis are essential for lowering rejection and rework, according to research.

2. Improvement in Process Consistency

One of the most important goals of quality assurance in Indian foundry industries is process consistency improvement. Several interrelated steps, including pattern creation, mold preparation, melting, pouring, solidification, fettling, and finishing, are involved in foundry operations. The final casting quality can be directly impacted by changes in any of these phases. To guarantee flawless production, factors such as sand moisture content, mold hardness, pouring temperature, molten metal chemical composition, gating design, and cooling rate must be kept

within predetermined bounds. Defects such as blowholes, shrinkage cavities, porosity, and dimensional errors are frequently caused by inconsistent control of these parameters [3], [12]. Foundries can attain stable and consistent production conditions by putting in place standard operating procedures, process monitoring systems, statistical quality control tools, and in-process inspection techniques. In addition to lowering rejection and rework, improved process consistency significantly boosts output, shortens cycle times, and guarantees consistent product quality across several manufacturing batches [10], [14]. For Indian foundries engaged in high-volume manufacturing industries like heavy engineering and automobiles, this is especially crucial. Foundry operations involve multiple process parameters:

- Sand moisture content
- Metal composition
- Pouring temperature
- Mold hardness
- Cooling time

Even minor variations can lead to product failure. Quality assurance ensures process standardization through SOPs, control charts, and in-process inspection.

3. Customer Satisfaction and Export Competitiveness

The quality standards upheld in foundry industries have a direct impact on export competitiveness and customer satisfaction. Indian foundries are selling cast components to both domestic and foreign markets as a result of growing globalization, especially in industries like automotive, aircraft, railroads, and industrial machinery. Strict dimensional tolerances, mechanical qualities, surface finish specifications, international certification standards like ISO 9001, and industry-specific quality standards are all demanded by global consumers [6], [21]. Superior castings result in increased product performance, decreased field failures, and increased dependability, all of which directly boost client confidence and long-term business partnerships.

Furthermore, as poor quality can lead to order rejection, financial losses, and harm to India's reputation in the market, maintaining consistent product quality is crucial to boosting the country's export potential. Thus, strong quality assurance systems and quality-focused manufacturing techniques are essential for raising customer satisfaction and boosting Indian foundry companies' ability to compete internationally. Indian foundries are increasingly catering to export markets and international OEMs. International clients require adherence to Six Sigma quality standards, ISO standards, and zero-defect manufacturing principles. A strong QA framework increases client trust by improving surface polish, dimensional correctness, and dependability.

The growing demand for high-precision, flawless cast components in both domestic and foreign markets has made quality assurance a crucial requirement for the Indian foundry sector. In industries where dimensional accuracy, metallurgical integrity, and mechanical strength are crucial, such as automotive, aircraft, railroads, agriculture,

construction, defense, and heavy engineering, the foundry industry provides essential components. Financial losses, customer unhappiness, and component failure could result from any reduction in product quality. In order to guarantee consistent product performance and industrial competitiveness, a strong quality assurance system is therefore more important than ever.

The high prevalence of casting flaws is one of the main justifications for Indian foundries' emphasis on quality assurance. Inadequate control of process parameters often results in common defects in casting operations, including blowholes, porosity, shrinkage cavities, cold shuts, sand inclusions, and surface blemishes [3], [9]. These flaws raise scrap production, rework expenses, and production delays in addition to decreasing the product's functional dependability. From raw material inspection to final product testing, quality assurance aids in the identification of problem causes at every stage of manufacturing. Foundries can greatly lower rejection rates and increase overall production efficiency by putting preventive quality measures into place [1], [10].

Process consistency is another crucial factor. A number of interrelated processes, including pattern creation, mold preparation, melting, pouring, solidification, fettling, and finishing, are involved in foundry manufacture. Casting quality can be directly impacted by changes in variables including sand moisture, mold hardness, pouring temperature, chemical composition, and cooling rate [12], [20]. Through standard operating procedures, control charts, and in-process inspection techniques, quality assurance systems guarantee that these parameters are continuously checked and kept within predetermined bounds. This lowers output variability and increases process reliability.

The Indian foundry business, particularly the MSME sector, frequently faces issues with antiquated machinery, a shortage of qualified labor, and a slow uptake of high-quality, contemporary tools [6], [7]. In these situations, quality assurance provides a methodical framework for workforce development, process standardization, and ongoing improvement.

It has been demonstrated that implementing approaches like Six Sigma, Lean Six Sigma, and Total Quality Management increases output, lowers errors, and raises customer satisfaction [5], [8], and [19]. By adhering to strict export regulations and quality standards, these quality-centric strategies help foundries compete successfully in international markets.

Table I: Indian Foundry Industry and Quality Need

Sl. No.	Parameter	Data	Significance
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1	Total foundry units in India	4,500–5,000 units	Indicates large industrial base, mostly MSMEs
2	Global rank	2nd largest producer	Shows global competitiveness of Indian foundry sector
3	Annual casting production	15.16 million MT (2023–24)	Reflects high production volume and need for strict quality control
4	Industry revenue	USD 21.0 billion	Highlights economic importance
5	Export value	USD 4.11 billion	Quality standards directly affect exports
6	Employment generated	2.0 million	Includes direct and indirect workforce
7	Small-scale units share	~80–85%	Shows MSME dominance and quality challenges
8	Growth rate	6–7% annually	Indicates expansion and modernization need
9	Automotive sector share	32%	Major demand sector requiring high precision
10	Internationally accredited units	~500 units	Indicates scope for broader QA adoption

Sustainability and long-term industrial growth are intimately related to quality assurance. The environmental impact of remelting processes is reduced, energy consumption is decreased, and raw material waste is decreased when faults and rework are reduced [21]. This supports both environmental and economic sustainability, which is becoming more and more crucial in contemporary production processes. As a result, the adoption of quality assurance procedures is not only technically necessary but also strategically necessary for the long-term development of the Indian foundry sector. The industrial significance of the Indian foundry sector is evident from the figures in Table I. With an annual production of 15.16 million metric tonnes and a revenue of USD 21 billion, India has become the world's second-largest casting manufacturer, producing between 4,500 and 5,000 units. Nearly 80–85% of units are in the small-scale industry, which emphasizes how urgently standardized quality assurance systems, process monitoring, and quality-centric techniques are needed to increase productivity and lower errors.

The need for rigorous quality control systems is further highlighted by the industry's heavy reliance on export markets and precision-demanding industries like the automobile sector.

IV. QUALITY-CENTRIC APPROACHES FOR SUSTAINABLE GROWTH

1. Statistical Quality Control (SQC)

One of the best quality-centric methods for monitoring, controlling, and enhancing manufacturing processes in the foundry industry is statistical quality control (SQC). It entails using statistical techniques to examine process variation and keep product quality within predetermined bounds. Important variables that need to be continuously monitored in foundry operations include pouring temperature, mold hardness, sand moisture content, chemical composition, and cooling pace. Control charts, histograms, Pareto analysis, process capacity studies, and cause-and-effect diagrams are examples of SQC tools that assist in locating anomalous variations and the underlying causes of faults [10], [14]. Foundries can identify process irregularities early on and take corrective action before faults arise by employing these technologies. This promotes sustainable industrial growth by increasing process stability, lowering rejection rates, and improving casting quality uniformity. SQC tools such as:

- Control Charts
- Pareto Analysis
- Histograms
- Cause-And-Effect Diagrams
- Process Capability Analysis

These tools help in monitoring process performance and identifying abnormal variations and enable data-driven decision-making and continuous quality improvement

2. Six Sigma and DMAIC Methodology

Six Sigma is a data-driven approach to quality management that aims to attain near-perfect quality levels by minimizing process errors and lowering variability. Six Sigma is frequently applied in the foundry industry to solve productivity problems, process inefficiencies, and recurrent casting flaws. A methodical approach to continuous improvement is offered by the DMAIC framework, which stands for Define, Measure, Analyze, Improve, and Control. Important quality problems including porosity and shrinkage faults are found during the Define phase. Defect rates and pertinent process data are gathered during the Measure phase. Using statistical and analytical methods, the Analyze phase focuses on identifying the underlying reasons of quality issues. Corrective actions are carried out during the Improve phase, and the Control phase makes sure that gains are maintained over time [5], [8], and [19]. Six Sigma and DMAIC dramatically lower rejection rates and increase production efficiency, according to several studies conducted in Indian foundries [6, 7, 11].

Six Sigma is widely used to reduce process defects and improve yield. The DMAIC framework includes:

- Define – identify quality issues
- Measure – collect defect data
- Analyze – determine root causes
- Improve – implement corrective actions
- Control – sustain improvements

This method is highly effective in foundry environments where defect minimization is a priority. Indian MSME manufacturing studies have shown measurable process improvements through Six Sigma deployment.

3. Total Quality Management (TQM)

Total Quality Management (TQM) is an all-encompassing management strategy that emphasizes ongoing improvement in all organizational operations with each employee's active participation. TQM places a strong emphasis on quality throughout the whole manufacturing process in the foundry industry, from the acquisition of raw materials to final inspection and customer delivery. It incorporates concepts like leadership commitment, supplier quality management, employee involvement, customer focus, and continuous process improvement [14], [19]. Defect avoidance becomes a shared responsibility in an organization with a quality-oriented culture thanks to TQM. Because it enhances customer satisfaction, staff skill development, communication, and standardization, this strategy is very advantageous for Indian foundries. TQM greatly enhances long-term industrial sustainability and competitiveness by promoting a culture of continuous improvement. TQM promotes organization-wide participation in quality enhancement. It includes:

- Employee Involvement
- Supplier Quality Management
- Continuous Training
- Preventive Maintenance
- Customer feedback systems

This quality-centric culture supports long-term sustainability.

4. Industry 4.0 and Smart Foundry Systems

The current transformation of conventional foundry operations through digital technologies and intelligent automation is exemplified by Industry 4.0 and smart foundry systems. This method incorporates automated inspection systems, artificial intelligence, machine learning, real-time data monitoring, Internet of Things (IoT) sensors, and predictive maintenance into foundry manufacturing processes. Continuous monitoring of vital parameters such furnace temperature, mold conditions, metal composition, and defect occurrence is made possible by smart foundry systems [16]–[18]. Predictive analytics helps avoid equipment failures and process deviations, while sophisticated AI-based defect detection systems can detect surface and interior casting faults with high accuracy. These technologies increase overall product quality, minimize waste, decrease downtime, and improve process reliability. Modern quality assurance in foundries is increasingly supported by:

- IoT sensors
- real-time temperature monitoring
- automated defect detection

- predictive maintenance
- KPI dashboards

Recent studies show that KPI-based digital quality systems significantly improve energy efficiency, process stability, and sustainability outcomes in foundries.

V. ROLE IN SUSTAINABLE GROWTH

Because they promote operational, environmental, and economic sustainability, quality assurance and quality-centric techniques are essential to the long-term development of the Indian foundry industry. Effective quality systems cut manufacturing costs and increase profitability by reducing errors, scrap creation, rework, and production downtime. Consistent product quality also enhances customer confidence, repeat orders, and export competitiveness, thereby strengthening long-term industrial growth [6], [21]. Defect avoidance and process optimization cut emissions, waste less raw materials, and use less energy during remelting, all of which are critical for energy-intensive foundry operations [1], [20].

Additionally, effective resource management, enhanced process consistency, and the use of contemporary digital technologies like intelligent quality control systems, predictive maintenance, and real-time monitoring all contribute to sustainable growth [16]–[18]. These methods not only increase operational effectiveness but also bring foundry industries into line with Industry 4.0 and green production goals. Thus, in Indian foundry sectors, quality-centric techniques provide a strategic basis for attaining long-term resilience, global competitiveness, and sustainable industrial development. Quality assurance directly contributes to sustainability through:

Economic Sustainability

Effective quality assurance and process optimization techniques that lower production costs and boost profitability are key to achieving economic sustainability in India's foundry industry. Foundries may drastically reduce operating costs and enhance resource efficiency by reducing defects, scrap, rework, and machine downtime. Six Sigma, Lean manufacturing, and statistical quality control are examples of quality-centric strategies that improve customer satisfaction and export competitiveness by increasing production efficiency and product uniformity. As a result, the industry experiences steady revenue growth and long-term financial stability [6], [21].

- Reduced Rejection Cost
- Lower Rework Expenses
- Improved Productivity
- Higher Profit Margins

Environmental Sustainability

One significant result of quality-centric manufacturing in foundry industries is environmental sustainability. Better

process control minimizes energy consumption and carbon emissions by reducing material waste, poor castings, and the need for remelting. Utilizing raw materials like metal, sand, and binders effectively also reduces industrial waste and pollution in the environment. Green manufacturing and sustainable industrial development are further supported by the use of energy-efficient production methods and intelligent monitoring systems [1], [20].

- Minimized Emissions
- Lower Sand Waste
- Lower Energy Consumption
- Reduced Metal Scrap

Social Sustainability

Stable employment opportunities, employee skill development, and increased workplace safety all contribute to the foundry industries' social sustainability. Quality assurance systems enable employees to participate in continuous improvement initiatives, promote safer operating methods, and lessen accidents brought on by process failures. Employee competency and productivity are increased through training programs pertaining to contemporary, high-quality tools and digital technologies. Furthermore, a healthy foundry industry supports social and economic growth by creating a significant number of direct and indirect jobs [13], [19].

- Safer Work Practices
- Skill Enhancement
- Employment Stability

This aligns with sustainable manufacturing and Industry 4.0 objectives.

VI. CHALLENGES IN INDIAN FOUNDRIES

Despite its importance, many Indian foundries still face:

1. Inadequate Quality Awareness

One of the biggest issues facing many Indian foundry industries, particularly small and medium-sized businesses, is inadequate quality awareness. In many instances, quality is still not seen as a process-oriented preventive system, but rather as a final inspection activity. This lack of knowledge frequently leads to inconsistent process control, poor adherence to standard operating procedures, and increased defect rates. Sustainable industrial growth requires raising knowledge of the significance of quality assurance, continuous improvement, and customer-focused manufacturing [6], [19].

2. Lack Of Skilled Manpower

The performance of Indian foundries is also significantly impacted by a shortage of skilled labor. Technical proficiency in fields including metallurgy, mold design, process control, defect identification, and equipment handling is necessary for foundry operations. However, many units struggle with a lack of skilled workers who can operate cutting-edge equipment and use high-quality, contemporary tools. Process errors, higher rejection rates,

and ineffective production methods are frequently caused by this skill mismatch [7], [13].

3. Outdated Equipment

In many foundry units, antiquated machinery and traditional manufacturing methods remain a significant constraint. The accuracy and consistency needed for contemporary manufacturing requirements might not be provided by older furnaces, molding equipment, and inspection systems. Process unpredictability, increased energy consumption, and higher maintenance costs are frequently the results of such equipment. Improving productivity and product quality requires modernizing equipment and implementing cutting-edge manufacturing technology [1], [20].

4. Resistance To Automation

In conventional foundry settings, resistance to automation is frequently seen because of worries about the cost of investments, worker adaption, and modifications to long-standing production methods. A lot of small-scale foundries are reluctant to use AI-based inspection systems, automated molding, and real-time monitoring. This opposition restricts foundries' capacity to compete in international markets and delays technical innovation. This difficulty can be addressed by raising awareness and showcasing long-term cost advantages [16]–[18].

5. Insufficient Data Collection

Insufficient data collection is a major barrier to effective quality assurance and process optimization. Without proper recording of process parameters, defect occurrence, machine performance, and production metrics, it becomes difficult to perform root-cause analysis and implement corrective actions. Data-driven methodologies such as Six Sigma and predictive maintenance depend heavily on accurate and continuous data collection. Therefore, establishing reliable data monitoring and reporting systems is essential for modern foundry quality management [5], [21]. Addressing these challenges requires management commitment and investment in quality systems.

VII. PROPOSED QUALITY FRAMEWORK FOR INDIAN FOUNDRY INDUSTRIES

An integrated quality framework is suggested for Indian foundry industries in order to guarantee sustainable growth, competitiveness, and constant product quality. The framework integrates contemporary quality-centric approaches and digital manufacturing technologies with traditional quality assurance practices. This framework's goal is to offer a scalable and organized paradigm that both large-scale foundries and MSME-based businesses can use. Before raw materials including metal charge, alloys, molding sand, binders, and additives are used in manufacturing, they must be inspected and tested according to the proposed framework. To avoid downstream flaws, input materials' chemical makeup and physical

characteristics must be kept within predetermined bounds. At this point, standardized supplier audits and vendor quality assessments should be included to guarantee uniformity in arriving materials.

Process quality control and monitoring are highlighted in the second layer. Critical factors such furnace temperature, sand moisture content, mold hardness, pouring rate, cooling time, and gating system performance need to be regularly monitored since foundry operations are extremely sensitive to process fluctuations. Everyday production monitoring should use statistical quality control (SQC) tools such Pareto charts, control charts, histograms, and process capability analysis. Process consistency and early detection of anomalous deviations are guaranteed by this layer [10], [14].

Six Sigma and continuous improvement techniques are combined in the framework's third layer. For persistent flaws including porosity, shrinkage, blowholes, and dimensional errors, the DMAIC method—Define, Measure, Analyze, Improve, and Control—should be applied as a methodical problem-solving technique [5], [19]. This layer concentrates on process standardization, corrective action planning, and root-cause analysis. Combining lean concepts can also minimize non-value-added operations, enhance workflow, and cut waste.

Workforce participation and Total Quality Management (TQM) are introduced in the fourth tier. It is impossible to accomplish sustainable quality improvement without management commitment and employee involvement. Workforce training, quality awareness initiatives, standard operating procedures, preventive maintenance plans, and cross-functional teamwork are all included in this layer [13], [14]. Employee skill development is especially crucial for Indian foundries, where a shortage of skilled labor is frequently a significant problem. Smart foundry systems and Industry 4.0 are integrated into the fifth layer. IoT-based sensors, real-time process monitoring, AI-driven defect identification, predictive maintenance, and KPI-based performance dashboards are all part of this contemporary layer [16]–[18], [21]. Automated data collecting, process visualization, early warning signals, and predictive quality assurance are all made possible by smart systems. In order to increase accuracy, decrease downtime, and promote sustainable manufacturing, this layer is extremely important.

Sustainability and performance evaluation are the main topics of the framework's last tier. Continuous monitoring is necessary for key performance measures such rejection percentage, energy consumption per casting, material utilization rate, production yield, frequency of customer complaints, and on-time delivery performance [21]. This layer establishes a direct connection between the goals of social, environmental, and economic sustainability and quality assurance. All things considered, the suggested integrated framework offers Indian foundry companies a thorough road map for achieving digital transformation,

process stability, defect-free production, and sustainable industrial growth.

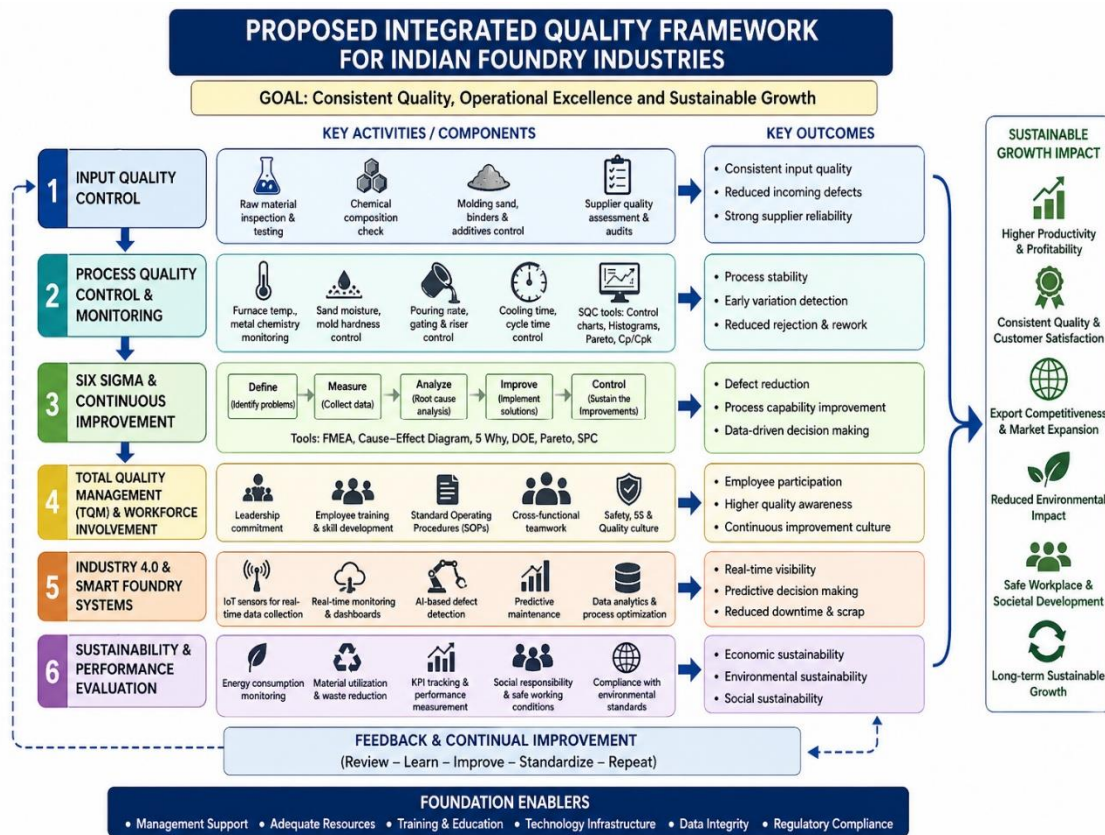


Fig. 1. Proposed Integrated Quality Framework for Indian Foundry Industries

A methodical, multi-layered strategy for attaining sustainable growth in the Indian foundry industries is presented by the suggested integrated quality framework shown in the figure. The framework starts with input quality control, which makes sure that supplier quality, chemical composition, molding sand, and raw materials are all checked before manufacturing starts. Critical factors including furnace temperature, sand moisture, pouring rate, and cooling time are regularly monitored using Statistical Quality Control (SQC) tools in the second layer, which focuses on process quality control and monitoring. In order to find flaws, examine their underlying causes, and put corrective measures in place for defect reduction and process capability enhancement, the third layer combines Six Sigma and continuous improvement techniques, especially the DMAIC cycle.

The fourth layer focuses on workforce involvement and Total Quality Management (TQM), emphasizing standard operating procedures, staff training, leadership commitment, and the establishment of a quality culture. Additionally, Industry 4.0 and smart foundry technologies, such as IoT sensors, AI-based defect detection, predictive maintenance, and data analytics for instantaneous decision-making, are integrated into the framework. Lastly, the sustainability and performance evaluation layer ensures

lower waste, increased profitability, safer workplaces, and long-term competitiveness by connecting quality assurance procedures with economic, environmental, and social sustainability. The figure illustrates how an integrated quality-centric framework may promote sustainable industrial development, export competitiveness, and ongoing improvement in Indian foundry industries.

VIII. SUMMARY AND DISCUSSION

The current study emphasizes how important quality assurance and quality-centric strategies are to raising the productivity and sustainability of the Indian foundry sector. The application of systematic quality procedures results in significant reductions in casting errors, scrap generation, and process variability, according to the literature review and analysis of prior industrial research. Applying Six Sigma, Lean Six Sigma, and statistical quality control methods led to a discernible drop in rejection rates and an increase in production output, according to a number of reviewed studies [5]–[8], [11]. This suggests that common foundry issues including porosity, shrinkage, blowholes, and surface flaws can be effectively addressed by established quality standards.

The findings from a number of case studies further imply that process improvement via parameter management directly affects product quality. Important variables affecting casting performance were found to include mold hardness, sand moisture content, pouring temperature, gating system design, and cooling time [3], [9], and [12]. The majority of faults are caused by a small number of process factors, according to studies utilizing Pareto analysis and cause-and-effect diagrams [10], [14]. This finding encourages the implementation of targeted quality improvement initiatives. This illustrates how process stability and consistency may be greatly improved by ongoing process parameter monitoring and control.

The effectiveness of Lean Six Sigma in increasing productivity and decreasing non-value-added operations is another significant finding from the research. In addition to minimizing defects, the integration of Lean principles with Six Sigma also lowers lead time, cycle time, and process waste [8]. This directly lowers costs and improves operational effectiveness, all of which are critical to Indian foundries' competitiveness, especially in the MSME sector.

A shift from traditional quality inspection to intelligent quality assurance systems is also revealed by the discussion of current studies. Artificial intelligence, deep learning-based defect identification, real-time process monitoring, and predictive maintenance are examples of advanced techniques that have demonstrated encouraging outcomes in automated quality control and defect prediction [16]–[18]. These smart manufacturing solutions lower the possibility of significant production losses and facilitate early defect diagnosis.

The findings clearly show that quality-centric strategies have positive effects on the economy and environment from a sustainability standpoint. During remelting operations, fewer rejections and rework result in lower energy and raw material consumption as well as lower emissions [21]. This improves the long-term growth potential of Indian foundry industry and directly supports sustainable manufacturing goals. Overall, the findings and discussion show that quality assurance systems greatly enhance product dependability, process efficiency, and sustainable industrial growth when combined with contemporary process control methods and digital technologies.

IX. CONCLUSION

For the Indian foundry industries to grow sustainably, quality assurance and quality-centric strategies are essential. Foundries may increase global competitiveness, decrease waste, and improve product reliability by implementing Six Sigma, TQM, and smart manufacturing technologies. A robust quality culture combined with cutting-edge technology is essential for the foundry industry's sustainable success.

The current study emphasizes how important quality assurance and quality-centric strategies are to the long-term development of the Indian foundry sector. Maintaining high

standards of product quality and process consistency is crucial for industrial competitiveness and customer satisfaction because the foundry industry is the foundation of major manufacturing areas like automotive, aerospace, railroads, construction, and heavy engineering. This paper's analysis and assessment of the literature make it abundantly evident that traditional inspection-based quality control is not enough to satisfy the increasing needs of contemporary manufacturing.

It has been demonstrated that casting defects, scrap generation, rework, and production variability may be considerably decreased by implementing structured quality approaches like Six Sigma, Lean Six Sigma, Total Quality Management (TQM), Statistical Quality Control (SQC), and root-cause analysis tools. Additionally, new possibilities for intelligent and sustainable foundry operations are presented by current developments in artificial intelligence, real-time monitoring, predictive maintenance, and KPI-based quality systems. In addition to improving process effectiveness and product dependability, these quality-centric strategies also support environmental sustainability, waste reduction, and energy conservation.

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