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Heated Chamber in Fused Deposition Modeling: A Content Analysis of Research Trends and Methodological Gaps (2020-2026)

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ABSTRACT

Heated chamber control has become a widely cited strategy for improving dimensional accuracy and mechanical performance in fused deposition modeling (FDM), yet the literature that establishes this claim has not itself been examined as a body of research. This study presents a focused content analysis of 13 peer-reviewed sources addressing heated chamber, enclosure, or thermal-environment control in FDM. Each source was coded by publication year and by whether it employed a structured statistical design method (Design of Experiments or Response Surface Methodology), a Statistical Process Control (SPC) framework, or a purely experimental or descriptive approach without a named statistical structure. Results show a modest but steady publication stream since 2020, with a small peak in 2023 and 2025, indicating that heated-chamber-specific research remains a comparatively narrow, still-emerging sub-literature within the broader FDM field. Only two of the thirteen sources employed a structured statistical design method, and only one employed an explicit Statistical Process Control framework; the remaining ten relied on experimental or descriptive approaches without a named statistical structure. This imbalance indicates that, despite widespread agreement in the literature that chamber temperature is a critical process variable, few studies have applied rigorous experimental design or process-monitoring frameworks to quantify or sustain its effects. The findings reinforce the case for statistically structured, process-control-oriented research on heated chamber control and illustrate how a small, focused literature corpus can be repurposed as a dataset for identifying methodological gaps in an applied engineering research area.

Keywords: heated chamber, fused deposition modeling, content analysis, design of experiments, statistical process control, research trends

INTRODUCTION

Fused deposition modeling (FDM) is highly sensitive to the thermal environment in which printing takes place. A growing body of literature attributes warping, poor interlayer adhesion, and inconsistent mechanical performance to uncontrolled ambient conditions (Fang et al., 2020; Tan et al., 2021; Thumsorn et al., 2023), and correspondingly recommends heated chamber or enclosure systems as a remedy (Boytsov et al., 2022). Despite the frequency with which this claim appears, the literature that supports it has not itself been examined as a body of research: how many studies address heated chamber control directly, when were they published, and what research methods do they rely on to support their conclusions.

Answering this question is useful for a reason that goes beyond any single material or machine: it indicates how mature and how methodologically rigorous a specific sub-topic of AM research currently is. A sub-literature dominated by descriptive or single-run experimental studies signals an area still in an exploratory stage, whereas one with a strong presence of structured statistical design and process-control studies signals a more mature, industrially reliable knowledge base. This distinction matters for researchers deciding where to focus future work, and for practitioners deciding how much confidence to place in existing recommendations.

This study addresses that question through a focused content analysis of heated-chamber-related FDM literature. Thirteen sources directly concerned with heated chamber, enclosure, or thermal-environment control were identified within the thesis's broader literature corpus and analyzed for publication trend and methodological orientation. The analysis does not report or evaluate the mechanical outcomes described in these sources; it treats the sources themselves as the unit of analysis.

Background

Heated chamber systems are reported to reduce warping and improve interlayer adhesion by maintaining a stable thermal environment during printing, an effect attributed to reduced cooling-rate gradients between deposited layers (Yu et al., 2021; Napolitano et al., 2022; Cozzolino et al., 2025). This mechanism is described consistently across the broader FDM literature, but the specific studies that isolate and test chamber or enclosure temperature as an experimental variable form a much smaller subset of that literature (Demir, 2025; Ekşi & Karakaya, 2025). Heated chamber operation also carries a trade-off against the energy-efficiency and eco-design goals increasingly expected of FDM systems, since sustained heating adds to the process's overall energy footprint (Ruiz-González et al., 2024). Understanding the size and methodological character of this subset is the starting point for identifying where future, more statistically rigorous research is needed, including the integration of Design of Experiments (DOE) for parameter optimization (Castillo et al., 2023) and Statistical Process Control (SPC) for sustaining consistency once optimal conditions are identified (Alatefi et al., 2023).

METHODOLOGY

Corpus and Source

The corpus consists of 13 peer-reviewed journal articles and conference papers that directly address heated chamber, enclosure, or thermal-environment control in FDM. Sources were included if their title or the surrounding discussion in the thesis explicitly concerned chamber, enclosure, or ambient/environmental temperature control during printing, as distinct from sources addressing only nozzle or bed temperature, material composition, or unrelated process parameters.

Coding Scheme

Each source was coded by (1) publication year, and (2) methodological orientation, categorized as structured statistical design (Design of Experiments or Response Surface Methodology named or clearly applied), Statistical Process Control or statistical quality monitoring, or experimental/descriptive (single- or multi-run experimental studies without a named statistical design or control framework). Coding was performed by the authors through close reading of each source's title and the discussion of it already present in the reviewed thesis. Table 1 presents the classification of the 13 corpus sources by reference, publication year, thematic focus, and methodological category.

Table 1: Classification of Heated-Chamber-Related Studies Included in the Analysis

References	Year	Focus	Method Category
Fang et al.	2020	Environmental temperature and humidity	Experimental
Tan et al.	2021	Cooling and temperature effects	Experimental
Yu et al.	2021	Auxiliary heat/interlayer bonding	Experimental
Boytsov et al.	2022	Need for heated chamber	Descriptive
Napolitano et al.	2022	PLA optimization	Experimental

Alatefi et al.	2023	Quality monitoring	SPC
Castillo et al.	2023	Thermal parameter optimization	DOE
Thumsorn et al.	2023	Enclosure temperature	Experimental
Ruiz-Gonzalez et al.	2024	Eco-design perspective	Descriptive
Cozzolino et al.	2025	Thermal effects	Experimental
Demir	2025	Parameter optimization	Experimental
Ekşi & Karakaya	2025	Process parameters	Experimental
Zurnacı & Alıcıoğlu	2026	Mechanical strength optimization	RSM

Scope and Limitations

As with any manually coded, single-corpus content analysis, this study does not replace a full database-driven bibliometric search using tools such as Scopus, Web of Science, or VOSviewer, and its findings should be read as indicative of a focused literature subset rather than an exhaustive survey of all heated-chamber-related FDM research. The small corpus size (N = 13) reflects the genuinely narrow scope of chamber-specific studies within the broader FDM literature rather than an artifact of incomplete search; it is itself a finding of the analysis. Independent verification through a full database search is recommended as future work.

RESULTS

Publication Trend

Table 2 and Figure 1 summarize the distribution of the 13 heated-chamber-specific sources by publication year. Publication activity has been modest but continuous since 2020, with small peaks of three sources each in 2023 and 2025. No year in the study window accounts for more than 23 percent of the corpus, in contrast to the sharper, more concentrated recent surge typically seen in the broader FDM/PLA literature. This suggests that heated-chamber-specific research has grown at a comparatively steady, incremental pace rather than experiencing a recent sharp acceleration.

Table 2 shows that publication activity on heated-chamber-related FDM research remained relatively modest but continuous throughout the 2020-2026 period. Only one study was identified in both 2020 and 2024, while two studies were published in 2021 and 2022. The highest publication output occurred in 2023 and 2025, with three publications each, representing 23.1% of the corpus per year. Although the annual volume remains small, the absence of publication gaps suggests sustained research interest in heated chamber control as a specialized topic within additive manufacturing. The findings indicate gradual rather than rapid growth, implying that heated-chamber-specific research remains an emerging niche area compared with broader FDM process-optimization research.

The relatively even distribution of publications across the study period also suggests that interest in heated chamber control has developed incrementally rather than through a sudden research surge. This pattern differs from many emerging additive-manufacturing topics that experience sharp publication growth following technological breakthroughs. Instead, heated chamber research appears to be driven by continuing practical concerns regarding dimensional stability, warping reduction, and interlayer bonding performance. The limited number of publications further supports the view that thermal-environment control remains underexplored despite its recognized importance in determining printed-part quality and mechanical performance.

Table 2: Distribution of Heated-Chamber-Related Sources by Publication Year (N = 13)

Year	No. of Sources	% of Corpus
2020	1	7.7%
2021	2	15.4%
2022	2	15.4%
2023	3	23.1%
2024	1	7.7%
2025	3	23.1%
2026	1	7.7%

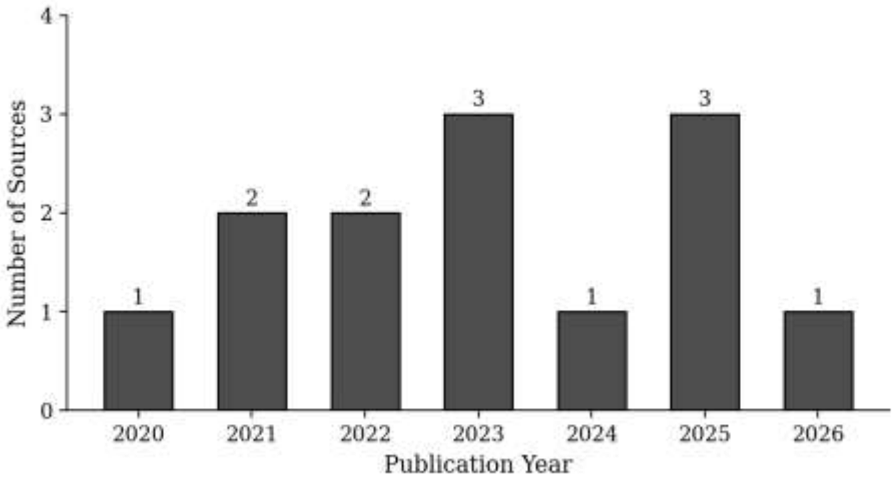

Figure 1: Publication Trend of Heated-Chamber-Related FDM Sources (2020-2026)

Methodological Orientation

Table 3 and Figure 2 report the methodological orientation of the corpus. Only two sources, Castillo, Monroy and Ahmad (2023) and Zurnacı and Alıcıoğlu (2026), employed a structured statistical design method, Design of Experiments and Response Surface Methodology respectively. Only one source, Alatefi, Al-Ahmari, AlFaify and Saleh (2023), employed an explicit Statistical Process Control or statistical quality-monitoring framework. The remaining ten sources, more than three-quarters of the corpus, relied on experimental or descriptive approaches, typically single- or multi-run comparisons of chamber or ambient conditions, without a named statistical design or control structure.

Table 3: Methodological Orientation of the Heated-Chamber Corpus (N = 13)

Methodological Orientation	No. of Sources	% of Corpus
Structured statistical design (DOE / RSM)	2	15.4%
Statistical Process Control (SPC)	1	7.7%
Experimental / descriptive only	10	76.9%

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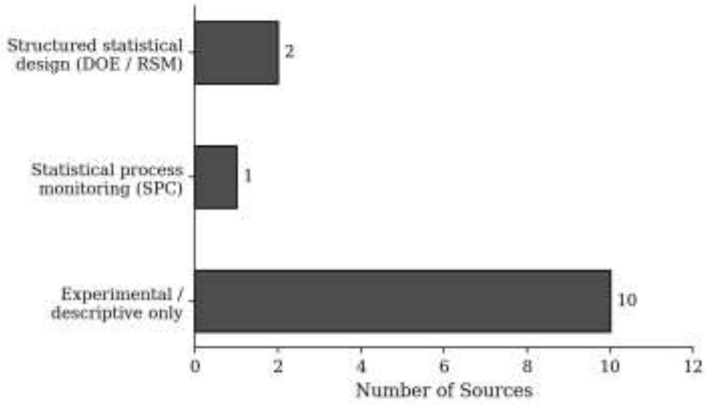

Figure 2: Methodological Orientation of Heated-Chamber-Related FDM Sources (N = 13)

DISCUSSION

The comparatively steady, low-volume publication trend suggests that heated chamber control, while frequently cited as important, has not attracted the same concentrated research attention as broader FDM parameter-optimization topics. This may reflect the practical difficulty of building and instrumenting a controlled heated chamber system, which requires custom hardware rather than only software or slicer-level parameter changes, making it a less accessible variable to study than, for example, infill density or print speed.

Another explanation for the comparatively small number of heated-chamber studies is the dominance of open-frame desktop FDM systems in academic laboratories. Many parameter-optimization studies focus on variables that can be changed directly through slicing software, such as layer thickness, infill density, print speed, or nozzle temperature. Heated chamber research, in contrast, often requires additional hardware development, temperature monitoring systems, and safety considerations. This higher experimental barrier may contribute to the slower growth of heated-chamber-specific research despite widespread recognition of its importance for part quality and mechanical performance.

The strong skew toward experimental and descriptive studies, and away from structured statistical design and process control, is the more consequential finding. It indicates that most existing evidence for the benefits of heated chamber control rests on comparisons between a small number of discrete conditions (Fang et al., 2020; Tan et al., 2021; Thumsorn et al., 2023) rather than on systematically modeled relationships between chamber temperature and outcome quality. Similarly, the near absence of Statistical Process Control applications suggests that even where optimal chamber conditions have been proposed (Yu et al., 2021; Demir, 2025), few studies have examined whether those conditions can be sustained consistently over repeated production runs, a question that matters as much for industrial adoption as the initial optimization itself (Alatefi et al., 2023).

The dominance of experimental studies without structured statistical frameworks suggests that much of the available evidence remains local and condition specific. While many authors report improvements in tensile strength, dimensional stability, and interlayer bonding under elevated chamber temperatures, these conclusions are often based on a limited number of parameter combinations. Without formal DOE approaches, it becomes difficult to quantify factor interactions, estimate response surfaces, or identify truly optimal operating regions. Consequently, knowledge accumulation in this field remains fragmented, making comparisons across studies difficult. The limited use of Statistical Process Control is particularly noteworthy because additive manufacturing is increasingly transitioning from prototyping toward production-oriented applications. Process optimization alone does not guarantee industrial reliability; parameter settings must also remain statistically stable across repeated production runs. The near absence of SPC-based studies therefore represents a significant methodological gap between laboratory-scale experimentation and industrial implementation.

These findings directly support the rationale for research that integrates Design of Experiments with Statistical Process Control specifically for heated chamber temperature, treating chamber control not only as a parameter to optimize once but as a process variable to monitor and sustain. They also illustrate a broader methodological point: a small, precisely scoped literature corpus, even one drawn from a single thesis's review chapter, can

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still yield a clear and useful characterization of a sub-field's maturity when it is analyzed systematically rather than only narratively.

Future Research

Based on the observed methodological imbalance, future heated-chamber research should move beyond one-factor-at-a-time experimentation and adopt integrated optimization-monitoring frameworks. DOE and Response Surface Methodology can be employed to establish predictive relationships between chamber temperature and critical quality characteristics, while SPC can be used to evaluate process stability under repeated manufacturing conditions. Future studies should also investigate the interaction between chamber temperature and other thermal variables, including nozzle temperature, bed temperature, cooling-fan settings, and environmental humidity. Expanding such investigations would contribute to the development of reliable process windows suitable for industrial-scale additive manufacturing.

CONCLUSION

This study examined 13 peer-reviewed sources specifically addressing heated chamber, enclosure, or thermal-environment control in FDM to characterize the publication trend and methodological maturity of this sub-literature. Publication activity has grown steadily but modestly since 2020, and most sources rely on experimental or descriptive approaches rather than structured statistical design or process control methods. Only two sources applied Design of Experiments or Response Surface Methodology, and only one applied a Statistical Process Control framework. These findings indicate that heated chamber control remains an under-formalized area of FDM research relative to its frequently cited practical importance, and they support continued research that combines experimental design with ongoing statistical process monitoring for chamber temperature specifically. Beyond the specific topic of heated chamber control, the study demonstrates how targeted content analysis of a narrowly defined literature corpus can provide useful insights into the methodological maturity of an emerging engineering research area. As with any single-corpus content analysis, a larger, database-driven bibliometric replication is recommended to confirm these patterns at scale.

Ethical Considerations

Ethical Approval: This study analyzes previously published, publicly available literature and secondary bibliographic data; it does not involve human subjects, animals, or primary data collection, and therefore did not require ethical approval.

Conflict of Interest: The authors declare no conflict of interest.

Data Availability Statement

The list of 13 coded sources and their classification (publication year, methodological category) is available from the corresponding author upon reasonable request.

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