

**Optimizing Semiconductor Yield Prediction: A  
Comparative Study of Traditional Machine  
Learning Approaches**

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**THIS REPORT IS SUBMITTED IN FULFILMENT  
OF THE REQUIREMENT FOR THE  
BACHELOR'S DEGREE IN SCIENCE WITH  
HONORS**

**FACULTY OF SCIENCE AND NATURAL  
RESOURCES  
UNIVERSITI MALAYSIA SABAH**

**2026**

**UNIVERSITI MALAYSIA SABAH**

**BORANG PENGESAHAN STATUS TESIS**

OPTIMIZING SEMICONDUCTOR YIELD PREDICTION: A COMPARATIVE STUDY OF TRADITIONAL MACHINE LEARNING APPROACHES

Judul Tesis

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## **DECLARATION OF THESIS**

Title of thesis

OPTIMIZING SEMICONDUCTOR YIELD PREDICTION: A COMPARATIVE STUDY OF TRADITIONAL MACHINE LEARNING APPROACHES

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## **ABSTRACT**

## **ABSTRAK**

## **ACKNOWLEDGMENT**

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## **LIST OF ABBREVIATIONS**

AVT	\AVT — Auditory Vigilance Task (yes)
BMM	\BMM — Bio-Mathematical Models (no)

# CHAPTER 1

## INTRODUCTION

### 1.1 Background

Semiconductor manufacturing underpins contemporary technological systems, and continued device scaling has increased process complexity and tightened tolerances across fabrication steps. In this context, maintaining high yield and consistent product quality is essential for sustaining profitability and industrial competitiveness (Adly et al., 2015; Chen et al., 2000). Because wafer fabrication involves large volumes of material and tightly coupled process stages, even modest yield degradation can translate into substantial cost impacts through scrap, rework, delayed delivery, and reduced effective capacity (Ahmed et al., 2025).

In semiconductor manufacturing, yield denotes the proportion of functional dies relative to the total number of dies produced on a wafer. Yield analysis therefore concerns both identifying yield loss events and understanding the process conditions and defect mechanisms that drive them (Ashby et al., 2024). Modern fabrication lines are instrumented with extensive in-line sensors and metrology, producing high-dimensional and heterogeneous data streams that reflect complex interactions among equipment, materials, and environmental factors (Akpabio et al., 2021; Aridas et al., 2025). However, conventional manufacturing oversight approaches—including manual inspections and static statistical process control—may be insufficient to capture nonlinear relationships, subtle interactions, and time-varying behavior present in such data (Adipraja et al., 2024; Amuru et al., 2023).

Machine learning methods provide a data-driven avenue to model these complex relationships, enabling predictive analytics for early identification of yield risk and supporting more proactive process control (Chang et al., 2024; Chen & Toly, 2018). When integrated with sensor-based monitoring, these techniques can improve the timeliness and

consistency of decision-making by learning patterns associated with yield loss and by filtering variability that obscures weak signals in traditional analyses (Ahmed et al., 2025; Amuru et al., 2023).

## **1.2 Importance and Relevance of Yield Analysis**

Early and accurate identification of yield loss drivers is essential for sustaining the reliability and economic performance of semiconductor fabrication lines. Robust yield analysis supports timely interventions—such as tool tuning, recipe adjustment, or targeted maintenance—thereby reducing scrap, minimizing rework and downtime, and improving overall equipment effectiveness (Ahmed et al., 2025; Chen & Toly, 2018; Chen et al., 2000). These benefits are amplified in high-volume manufacturing, where small shifts in process stability can propagate across many wafers and lead to substantial cumulative losses (Baek et al., 2024).

The significance of yield analysis has increased further with the adoption of extensive in-line sensing and metrology. Continuous data streams provide an opportunity for earlier detection of process excursions and more consistent decision-making than periodic manual checks, provided that the data can be interpreted effectively (Akpabio et al., 2021; Aridas et al., 2025). Consequently, data-driven approaches that can reliably extract actionable signals from complex manufacturing data are central to improving yield, maintaining product quality, and supporting dependable supply for downstream, performance-critical electronic systems (Ahmed et al., 2025; Amuru et al., 2023).

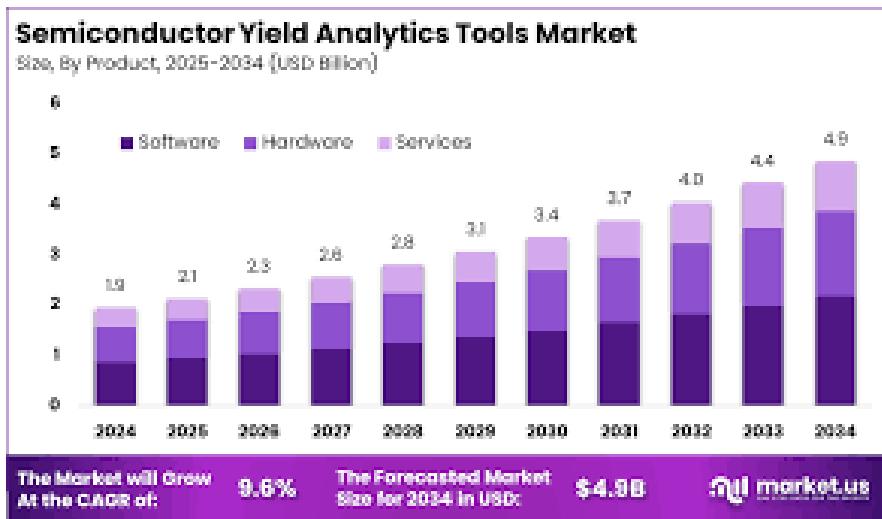
### **1.2.1 Local Perspective**

In local manufacturing environments, yield losses often translate directly into extended cycle time, increased rework, and higher test and packaging costs, making rapid diagnosis and prediction especially valuable for maintaining competitiveness. Practical deployment further requires models that can operate on high-dimensional sensor streams

and remain robust under process drift, missing values, and class imbalance (Park et al., 2022, 2024). Prior studies demonstrate that machine learning can support yield prediction and diagnosis across key production stages, including wafer acceptance testing and final test, thereby enabling earlier containment of yield excursions and more targeted corrective actions (Fan et al., 2022; Jiang et al., 2020, 2021). In addition, explainable and expandable modeling frameworks are increasingly emphasized to support trust and actionable decision-making on the factory floor (Lee et al., 2023). Accordingly, this study focuses on comparing traditional machine learning approaches under realistic data constraints, aligning predictive performance with the operational needs of local semiconductor production.

### **1.2.2 Market Size and Investment Trends in Semiconductor Yield Analytics**

Beyond its operational importance, yield prediction and optimization has become an active area of industrial investment as semiconductor firms expand data infrastructures for Industry 4.0 manufacturing and pursue faster, more reliable decision cycles. Recent literature highlights growing adoption of data-driven process monitoring, virtual metrology, and AI-enabled process control as practical pathways to reduce measurement latency, improve fault diagnosis, and shorten yield ramp-up (Hsiao et al., 2024; Maitra et al., 2024; Xu, Hong-Wei, et al., 2022). In parallel, the rapid evolution of machine learning architectures for defect recognition and yield-related inference reflects sustained R&D attention toward manufacturing analytics capabilities that can generalize across tools, products, and operating conditions (Chen et al., 2024; Kim, Tongwha, et al., 2023; Lin et al., 2025). These trends motivate the present project flow—data preprocessing, systematic feature selection, and comparative evaluation of traditional machine learning models—as a pragmatic route to obtain deployable performance improvements while maintaining interpretability and robustness in real production settings (Lee et al., 2023; Park et al., 2024).



**Figure 1.1. Illustrative market and investment interest in semiconductor yield analytics tools.**

### 1.2.3 Economic Impact of Yield-Loss Events and Manufacturing Failures

Yield degradation in semiconductor manufacturing is not merely a technical concern; it carries substantial economic consequences through scrap, rework, delayed deliveries, and unplanned tool downtime. Because wafer fabrication is highly capital intensive, even short disruptions or localized process excursions can propagate across lots and reduce effective capacity, amplifying losses at high volume (Adipraja et al., 2024; Ahmed et al., 2025). Empirical studies show that data-driven fault detection, virtual metrology, and yield prediction can provide earlier warning of abnormal equipment and process conditions, enabling more targeted maintenance and faster containment actions before defects accumulate (Chang et al., 2023; Kim, Eunji, et al., 2023; Xu, Hong-Wei, et al., 2022). From an operational standpoint, these capabilities reduce the likelihood of extended recovery periods during yield ramp-up and help stabilize performance under drift and variability (Park et al., 2024; Xu et al., 2024). Therefore, the project workflow adopted in this study—preprocessing high-dimensional sensor data, selecting informative features, and benchmarking traditional machine learning models—is motivated by the need to deliver reliable predictive signals that translate into measurable cost avoid-

ance and improved manufacturing resilience (Lee et al., 2023).

#### **1.2.4 Government Funding and Policies Supporting Smart Manufacturing Analytics**

Public policy and funding priorities increasingly encourage the digital transformation of manufacturing, including investments in sensing, data infrastructure, and analytics capabilities that strengthen quality and reliability in high-value industries such as semiconductors. In this context, data-driven monitoring, virtual metrology, and AI-assisted process control are widely recognized as enabling technologies for more resilient and efficient production systems (Hsiao et al., 2024; Lin et al., 2025; Maitra et al., 2024). At the same time, research trends reported in recent surveys and industrial studies emphasize the need for deployable machine learning solutions that remain robust under practical constraints—for example, missing values, drift, and heterogeneous data sources—which aligns with broader policy goals of improving productivity and reducing waste in advanced manufacturing (Chen et al., 2024; Park et al., 2024). These policy-driven directions provide additional justification for the present project flow, where systematic preprocessing and feature selection are used to produce reliable, interpretable predictive models that can be integrated into routine yield monitoring and decision support (Lee et al., 2023).

#### **1.2.5 Industry Initiatives and Data-Driven Yield Monitoring Programs**

Beyond policy signals, industry-led initiatives increasingly operationalize smart manufacturing analytics through end-to-end yield monitoring programs that combine in-line sensing, virtual metrology, and predictive modeling. Semiconductor fabs have long pursued data-centric monitoring frameworks to detect process excursions early and support continuous yield improvement, with more recent efforts emphasizing scalable data platforms and learning-based decision support (Kim, Eunji, et al., 2023; Nakata et al., 2017).

In particular, virtual metrology programs have matured as a practical mechanism for estimating quality variables without exhaustive physical measurements, enabling faster feedback for control and diagnosis (Kang et al., 2017; Maitra et al., 2024; Xu, Hong-Wei, et al., 2022). Complementing these approaches, advances in AI-enabled process control and digital-twin-oriented optimization highlight a broader industrial push toward closed-loop, data-driven improvement cycles that can adapt to drift and tool-to-tool variability (Gentner et al., 2024; Hsiao et al., 2024; Lin et al., 2025).

Within this landscape, a recurring implementation requirement is that analytics models must be accurate, robust, and deployable under production constraints such as high dimensionality, missing data, and shifting operating regimes (Ou et al., 2024; Park et al., 2024). The workflow adopted in this study aligns with these industrial programs by prioritizing reproducible preprocessing, systematic feature selection, and comparative evaluation of traditional machine learning methods that are easier to validate and integrate into existing monitoring pipelines (Lee et al., 2023).

### **1.3 Existing Approaches and Challenges**

Existing yield analysis approaches in semiconductor manufacturing range from traditional statistical monitoring and rule-based diagnostics to modern machine learning-driven frameworks that leverage high-dimensional sensor and metrology data. Early methods relied heavily on manual engineering analysis and classical process control, which remain useful for detecting gross shifts but can struggle with nonlinear interactions, multistage dependencies, and rapidly evolving process windows (Adly et al., 2015; Amuru et al., 2023; Chen et al., 2000). To improve sensitivity and automation, recent studies increasingly apply supervised learning, deep learning, and virtual metrology to predict yield outcomes and identify patterns associated with defect generation or equipment anomalies (Chang et al., 2023; Kim, Tongwha, et al., 2023; Xu, Hong-Wei, et al., 2022).

Despite these advances, several challenges continue to limit reliable deployment in pro-

duction settings. Semiconductor datasets are often noisy, heterogeneous, and imbalanced, with missing values and drifting distributions that can reduce model stability and cause optimistic results to fail when transferred across tools, products, or fabs (Park et al., 2022, 2024; M. Xu & Zhao, 2024). Moreover, high predictive accuracy alone may be insufficient if models do not provide actionable explanations for engineers or cannot be maintained as processes evolve (Chen et al., 2024; Lee et al., 2023). These constraints motivate this project’s workflow, which emphasizes robust preprocessing, systematic feature selection, and comparative evaluation of traditional machine learning models as a pragmatic balance between performance, interpretability, and generalizability.

### **1.3.1 Limitations of Traditional Methods**

Traditional yield diagnosis in semiconductor fabs has long depended on manual engineering review, rule-based screening, and classical statistical process control. While these approaches remain valuable for detecting obvious shifts, they increasingly struggle to scale with the volume, velocity, and heterogeneity of modern in-line sensing and metrology streams (Adly et al., 2015; Akpabio et al., 2021; Aridas et al., 2025). Because many traditional workflows assume a limited number of key variables and relatively stable operating regimes, they can be ill-suited to capturing the nonlinear interactions and multistage dependencies that characterize advanced process integration (Amuru et al., 2023; Chen et al., 2000).

A primary limitation of manual and heuristic-driven analysis is variability in interpretation and actionability. Engineering review often relies on locally tuned thresholds, informal rules, and tacit knowledge accumulated through experience. As a result, conclusions may differ across analysts, shifts, and fabs, and the rationale behind a decision may be difficult to standardize or audit (Amuru et al., 2023). This lack of consistency is particularly problematic when processes evolve quickly (e.g., recipe updates, tool matching changes, or product mix shifts), because re-tuning rule sets and control limits can lag behind manufacturing reality (Park et al., 2024).

Traditional methods can also be reactive rather than predictive. Classical SPC is typically effective at flagging large deviations after they occur, but it may provide limited early warning for subtle drift, precursor signatures, or compound failure modes that develop over multiple steps (Adly et al., 2015; Xu, Hong-Wei, et al., 2022). In high-volume manufacturing, where excursion containment time strongly influences the number of affected wafers, these delays can translate into increased scrap, rework, and extended recovery cycles (Ahmed et al., 2025; Maitra et al., 2024).

Robustness under realistic production conditions presents another persistent challenge. Noise, missing values, and heterogeneous sampling rates can obscure weak yield signatures and undermine fixed thresholds or static control limits, leading either to missed excursions or excessive false alarms (Park et al., 2022; Xu et al., 2024). Additionally, distribution drift and tool-to-tool variation can cause monitoring logic tuned on one time period or tool to degrade when transferred, which reduces reliability in deployment (Park et al., 2024; Xu et al., 2024).

Finally, traditional workflows often struggle with attribution when multiple interacting factors contribute to a single yield event. Root-cause analysis commonly becomes an iterative, labor-intensive process that requires cross-tool context and multivariate reasoning that is difficult to formalize with hand-crafted rules alone (Ou et al., 2024). When coupled with growing expectations for explainability and maintainability in deployed analytics, these limitations motivate more automated and data-driven alternatives that can learn from high-dimensional data while remaining interpretable and operationally usable on the factory floor (Chen et al., 2024; Lee et al., 2023).

### **1.3.2 Challenges with Automated Methods**

Motivated by the limitations of manual and rule-based workflows, automated yield analytics based on machine learning and advanced signal processing have been widely adopted to improve consistency and to extract predictive signals from large-scale sensor and metrology data (Chang et al., 2023; Maitra et al., 2024; Xu, Hong-Wei, et al.,

2022). Nevertheless, automation introduces its own set of challenges that can limit reliability when models are deployed in production environments.

A central technical difficulty is representation learning and feature selection. High-dimensional fab data often contain redundant, weakly informative, or highly correlated variables, and naive use of all available signals can increase overfitting and reduce model stability (Akpabio et al., 2021; Park et al., 2022). While systematic feature selection can improve efficiency and interpretability, selecting features that remain meaningful across tools, product families, and time periods remains non-trivial, particularly under evolving process windows and tool matching changes (Ou et al., 2024; Park et al., 2024).

A second challenge concerns model selection and optimization. Different algorithms exhibit different sensitivities to class imbalance, noise, and nonlinear interactions, and model performance can vary substantially depending on preprocessing choices, hyper-parameter settings, and validation strategy (Park et al., 2022; Xu et al., 2024). In production settings, exhaustive tuning can be computationally expensive and may yield fragile configurations that perform well in offline experiments but degrade under drift or when transferred to a new toolset (Park et al., 2024; Xu et al., 2024).

Generalization and transferability are persistent barriers to dependable automation. Models trained on historical data may fail when the data distribution shifts due to equipment maintenance, recipe updates, chamber seasoning, or changes in product mix (Park et al., 2024; Xu et al., 2024). This is compounded by practical data issues such as missing values, heterogeneous sampling rates, and rare-event targets (e.g., low-yield excursions), which can cause optimistic training results to collapse in real deployment (Park et al., 2022). Consequently, robust evaluation protocols and adaptation mechanisms are often required to sustain performance beyond the original training context (Chen et al., 2024; Xu et al., 2024).

Finally, automated approaches must address interpretability and operational integration. Even accurate models may be of limited value if they cannot provide explanations that are actionable for process engineers, or if they are difficult to maintain as processes and data pipelines evolve (Chen et al., 2024; Lee et al., 2023). Ensuring that automated

methods deliver both reliable predictive performance and usable diagnostic insight remains a key research and engineering challenge for practical yield monitoring programs (Maitra et al., 2024; Ou et al., 2024).

## 1.4 Problem Formulation

This work frames yield analytics as a supervised learning problem defined over high-dimensional manufacturing data collected from in-line sensors and metrology. Each wafer-level (or lot-level) observation is represented by a vector of process variables, and the associated target describes the manufacturing outcome (e.g., a continuous yield value or a discrete yield state). The objective is to train a predictive model that remains accurate and stable under realistic production constraints, including noisy measurements, missing values, heterogeneous sampling, and distribution drift over time and across tools (Akpabio et al., 2021; Park et al., 2022, 2024; Xu et al., 2024).

From an operational standpoint, the formulation emphasizes three requirements. First, the modeling pipeline must be deployable on production data streams, which motivates robust preprocessing and handling of imbalance and rare-event behavior typical of yield-loss episodes (Ahmed et al., 2025; Park et al., 2022). Second, the learned model should support decision-making by enabling diagnosis or prioritization of suspected drivers, aligning predictive outputs with engineer workflows and maintainability expectations (Chen et al., 2024; Lee et al., 2023). Third, performance should be assessed using evaluation protocols that reflect transfer and drift scenarios, rather than relying solely on in-sample accuracy (Park et al., 2024; Xu et al., 2024).

### 1.4.1 Research Gap

Although the literature demonstrates the value of machine learning for yield prediction, fault detection, and virtual metrology, many studies evaluate a single algorithm or a narrow family of models on a specific dataset and report results under a fixed experimental setting (Chang et al., 2023; Maitra et al., 2024; Xu, Hong-Wei, et al., 2022).

This makes it difficult to determine the relative strengths and weaknesses of traditional machine learning methods under varying production conditions (e.g., differing noise profiles, sampling regimes, and tool-to-tool variation), and it limits confidence that reported performance will transfer to other tools, products, or time periods (Park et al., 2024; Xu et al., 2024).

A second gap concerns feature representation and its interaction with algorithm choice. Modern fabs generate heterogeneous measurements with complex dependencies, yet prior work often provides limited analysis of how alternative feature sets and selection strategies affect downstream model robustness, interpretability, and computational cost (Akpbio et al., 2021; Ou et al., 2024; Park et al., 2022). Because different learners can be sensitive to different representations, insufficient attention to feature engineering and selection can lead to models that appear accurate in controlled evaluations but become unstable under drift or missing data (Park et al., 2022; Xu et al., 2024).

Finally, there remains a practical gap between predictive performance and deployability. Industrial adoption increasingly requires models that are not only accurate but also explainable, auditable, and maintainable as processes evolve (Chen et al., 2024; Lee et al., 2023). However, systematic comparisons that jointly consider performance, robustness, and interpretability across realistic data constraints are still limited, motivating the comparative workflow adopted in this study (Maitra et al., 2024; Park et al., 2024).

#### **1.4.2 Problem Statement**

Based on the identified research gap, this study addresses three interrelated problems in semiconductor yield analytics. First, there is a need for a comprehensive and reproducible comparison of widely used machine learning algorithms for yield prediction and yield-loss identification, evaluated using consistent metrics (e.g., accuracy and F1-score for classification settings, and error measures for regression settings) together with computational cost considerations that affect on-line monitoring feasibility (Chang et al., 2023; Park et al., 2022; Xu, Hong-Wei, et al., 2022). Second, there is limited un-

derstanding of which feature representations and feature selection strategies are most effective for different learners when applied to high-dimensional sensor and metrology data, motivating a systematic investigation of feature subsets and selection procedures to identify robust and discriminative predictors while preserving interpretability (Akpabio et al., 2021; Lee et al., 2023; Ou et al., 2024). Third, there is a need to evaluate model generalizability under realistic transfer scenarios, including distribution drift over time and tool-to-tool or product-to-product variation, by testing models beyond their original training conditions to better quantify robustness and real-world applicability (Chen et al., 2024; Park et al., 2024; Xu et al., 2024).

## **1.5 Study Objectives**

This study aims (1) to identify an effective feature set for each traditional machine learning model by evaluating alternative feature combinations derived from the cleaned SECOM sensor/test variables, (2) to compare the yield-screening performance of multiple traditional algorithms (SVM, DT, RF, LR, and XGBoost) under a consistent, leakage-safe training and validation protocol, and (3) to assess model generalizability by evaluating final performance on a locked, independent test set that represents previously unseen manufacturing samples.

## **1.6 Scope of Work**

The scope of this thesis is limited to supervised binary yield screening using the publicly available SECOM dataset, where each observation is represented by a high-dimensional vector of anonymized sensor and test variables ( $F_1$ – $F_{590}$ ) and the target indicates pass/fail outcome. Specifically, the work comprises: (1) data ingestion and cleaning, including handling missing values and scaling under a strict no-leakage protocol; (2) stratified partitioning into a training set and a locked hold-out test set to support unbiased evaluation; (3) class-imbalance handling applied on the training data only; (4)

systematic feature selection to obtain compact and robust feature subsets suitable for high-dimensional manufacturing data; (5) comparative training and tuning of traditional machine learning classifiers (e.g., Logistic Regression, SVM, Decision Tree, Random Forest, and XGBoost) under a consistent validation protocol; and (6) evaluation using imbalance-aware metrics (precision, recall, F1-score, and ROC–AUC) with an explicit analysis of generalization on the independent test set.

This scope intentionally prioritizes reproducibility, leakage prevention, and deployable baseline modelling over domain-specific sensor semantics, because SECOM features are anonymized and direct process interpretability is therefore limited.

## 1.7 Organization of the Thesis

This thesis is structured as follows. Chapter 1 introduces the study background and motivation and defines the problem setting, objectives, and scope, thereby establishing the context and rationale for the work. Chapter 2 surveys related literature on yield analytics and manufacturing data-driven monitoring, summarizing established approaches and key challenges, and motivating the methodological choices adopted in this thesis. Chapter 3 describes the research methodology in detail, including data acquisition, pre-processing, feature construction and selection, model training, and the evaluation protocol, with emphasis on reproducibility of the experimental pipeline. Chapter 4 reports and discusses the experimental findings, including comparative model performance and the influence of feature choices on predictive behavior and robustness across datasets. Chapter 5 concludes by summarizing the main contributions and results, discussing practical implications for deployment in semiconductor manufacturing, and outlining directions for future work. Supplementary material is provided in the Appendix, including additional dataset information, methodological details, parameter settings, and extended results to support replication and further study.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Machine Learning in Semiconductor Yield Prediction and Yield Analytics

Semiconductor manufacturing is widely recognized as a complex and capital-intensive domain in which small deviations in process stability can translate into substantial yield loss and cost. As technology nodes shrink and process windows tighten, the volume and dimensionality of in-line sensor, metrology, and test data have increased to the point where manual inspection and purely rule-based statistical monitoring are often insufficient for timely diagnosis and intervention (Adly et al., 2015; Amuru et al., 2023; Ko et al., 2023; Sandru et al., 2022). Within this context, machine learning (ML) has become a central tool for converting heterogeneous manufacturing data into actionable predictions, supporting earlier identification of yield-limiting mechanisms and more systematic yield improvement (Jiang et al., 2021; Q. Wang & Huang, 2025).

In line with this thesis title (comparative study of traditional ML approaches for yield prediction), the literature in Section 2.1 is reviewed through a workflow consistent with the project's experimental pipeline: (i) acquisition of manufacturing datasets (equipment/process parameters, WAT/FT measurements, and yield indicators), (ii) preprocessing and representation of raw measurements into features, (iii) feature selection to reduce dimensionality and improve robustness, and (iv) benchmarking of multiple conventional ML models under consistent evaluation protocols. This flow reflects common industrial analytics practice, where deployability depends not only on accuracy but also on stability under noise, missing values, and drift (Akpabio et al., 2021; Park et al., 2022, 2024; Xu et al., 2024).

In yield-oriented analytics, prior work is commonly framed around three task families. First, classification predicts discrete yield-related outcomes (e.g., pass/fail, low-yield vs. normal-yield lots) from upstream measurements, which aligns with binary quality

screening used in high-volume manufacturing. Second, regression predicts continuous quality outcomes (e.g., yield percentage, parametric targets, or virtual metrology estimates) from process and test variables (Chen & Toly, 2018; Jiang et al., 2021; Xu, Hong-Wei, et al., 2022). Third, anomaly detection aims to identify rare process excursions or distribution shifts that can precede yield loss (Shin, Jin-Su, Kim, Min-Joo, Kim, et al., 2025; Shin, Jin-Su, Kim, Min-Joo, Lee, & Dong-Hee, 2025). The remainder of this chapter synthesizes prior work along these dimensions and highlights recurring challenges in generalizability, feature engineering, and benchmarking practices.

## **2.2 Overview of Traditional Machine Learning Algorithms in the Proposed Yield Prediction Workflow**

This section reviews prior studies that apply traditional machine learning algorithms to semiconductor yield prediction and yield analytics. Emphasis is placed on (i) how conventional models are positioned within a typical workflow (data acquisition from process, equipment, and test sources; preprocessing and feature engineering; model training and validation; and performance benchmarking), (ii) the motivations for selecting specific algorithms under manufacturing constraints (interpretability, computational efficiency, robustness to high dimensionality and noise), and (iii) findings from comparative studies that report performance trade-offs across models under consistent evaluation protocols.

### **2.2.1 Support Vector Machine (SVM)**

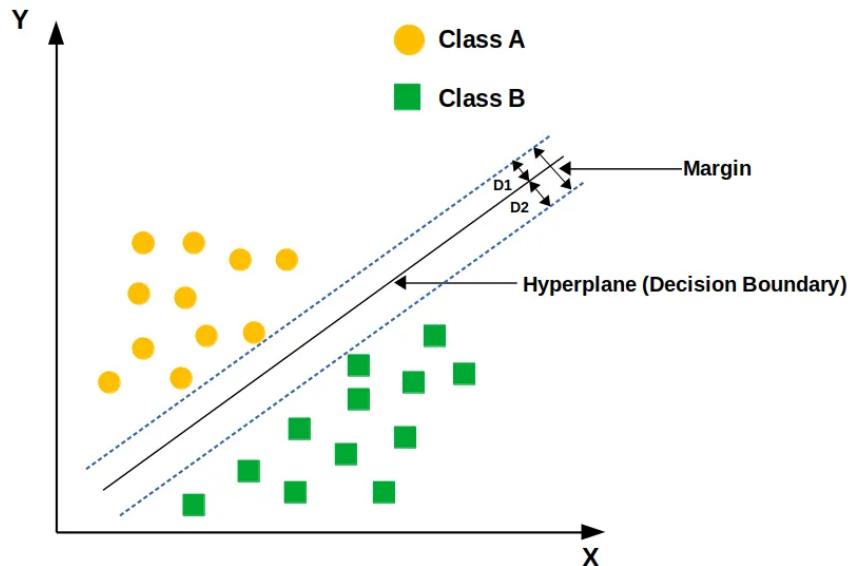
Support Vector Machines (SVMs) are a widely adopted class of supervised learning models in semiconductor yield analytics because they remain effective in high-dimensional settings and can represent non-linear decision boundaries through kernel functions. Conceptually, SVM learning seeks a maximum-margin separating hyperplane (or its regression analogue), which often provides strong generalization when the number of measured variables is large relative to the number of labeled samples available for model training (Yeh et al., 2024).

Within the yield prediction workflow, SVM-based models are commonly used for yield-related classification (e.g., quality screening and fault detection) and regression (e.g., virtual metrology and parametric prediction), where relationships between upstream process/test variables and downstream yield outcomes can be highly non-linear (Deivendran et al., 2025; Kim et al., 2022). One-Class SVM variants have also been applied for anomaly detection to flag potential process excursions and distribution shifts that precede yield loss (Shin, Jin-Su, Kim, Min-Joo, Kim, et al., 2025; Shin, Jin-Su, Kim, Min-Joo, Lee, & Dong-Hee, 2025). In addition, sparse formulations such as L1-regularized SVMs (L1-SVM) provide embedded feature selection, supporting more stable and interpretable models when manufacturing datasets contain many correlated sensors or test variables (Shaer et al., 2023).

Empirical results across yield-oriented studies further support the role of SVMs as strong baselines and competitive learners under realistic manufacturing constraints. For example, (Yeh et al., 2024) reported that combining SVM with mutual-information-based feature selection and simplified swarm optimization improved classification performance while reducing the number of retained features, illustrating how SVMs are frequently paired with feature selection to address dimensionality and noise. In lithography-related prediction tasks, (Xu et al., 2018) showed that SVM-based models can achieve comparable predictive quality to linear baselines while substantially improving computational efficiency, which is a practical consideration for high-throughput manufacturing analytics. In testing and quality screening, (Xama et al., 2023) demonstrated that SVM classifiers can improve defect escape detection with limited yield impact, and (Park et al., 2024) reported improved screening performance on the SECOM dataset when SVM was integrated with resampling and scaling strategies. For continuous outcome prediction, probabilistic support vector regression (PSVR) combined with Bayesian optimization has also been reported as effective for early quality prediction prior to burn-in, highlighting the flexibility of SVM variants for both classification and regression within yield prediction workflows (Ahmed et al., 2025).

Figure 2.1 illustrates a non-linear decision boundary generated by a kernel Support Vec-

tor Machine (SVM). The figure highlights SVM's ability to separate complex, overlapping data distributions by maximizing the margin between classes, which is advantageous for semiconductor yield prediction where relationships between process parameters and yield outcomes can be high-dimensional and non-linear.



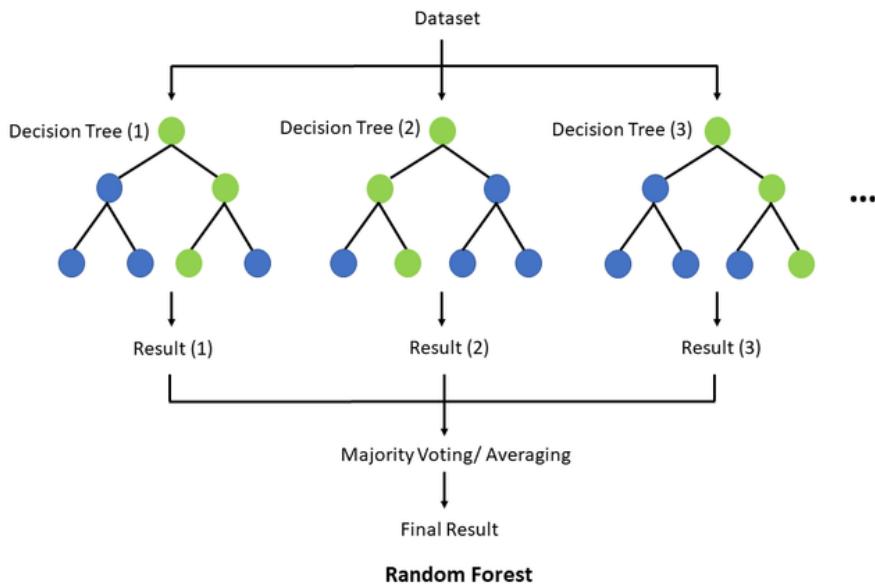
**Figure 2.1. Conceptual illustration of a non-linear decision boundary produced by a kernel Support Vector Machine (SVM).**

## 2.2.2 Random Forest (RF)

Random Forest (RF) is an ensemble learning method that aggregates predictions from multiple decision trees to improve generalization in both classification and regression. This bagging-based structure is well-suited to semiconductor yield analytics, where datasets are often high-dimensional, noisy, and characterized by non-linear feature interactions. In practice, RF is commonly adopted as a robust baseline model within yield prediction workflows because it requires limited distributional assumptions, provides stable performance under correlated inputs, and naturally supports variable-importance analysis to identify influential process and test factors (Deivendran et al., 2025; Hsieh

et al., 2025; Kim, Eunji, et al., 2023; Wang et al., 2023).

As shown in Figure 2.2, Random Forest combines multiple decision trees to enhance prediction stability and generalization, which is advantageous when dealing with noisy and high-dimensional semiconductor manufacturing data.



**Figure 2.2. Conceptual illustration of the Random Forest algorithm, where multiple decision trees are trained on random subsets of data and features and aggregated to form the final prediction.**

Empirical studies further highlight RF's effectiveness in yield-oriented applications. For example, (Kim, Eunji, et al., 2023) reported that RF-based models can support low-yield diagnosis by ranking influential equipment signals and excursion-related factors, enabling targeted process interventions. In broader manufacturing analytics, RF has been used to identify critical variable combinations and operational patterns associated with performance degradation, with feature importance serving as a practical bridge between prediction and actionable engineering insights (Hsieh et al., 2025; Wang et al., 2023). For continuous outcome modeling, (Lee et al., 2023) demonstrated that RF regression combined with explainability techniques can achieve competitive predictive accuracy while providing interpretable attributions, which is beneficial when models are

intended to inform decision-making in fab settings. Overall, these findings motivate the inclusion of RF in comparative benchmarking studies focused on robust and interpretable yield prediction.

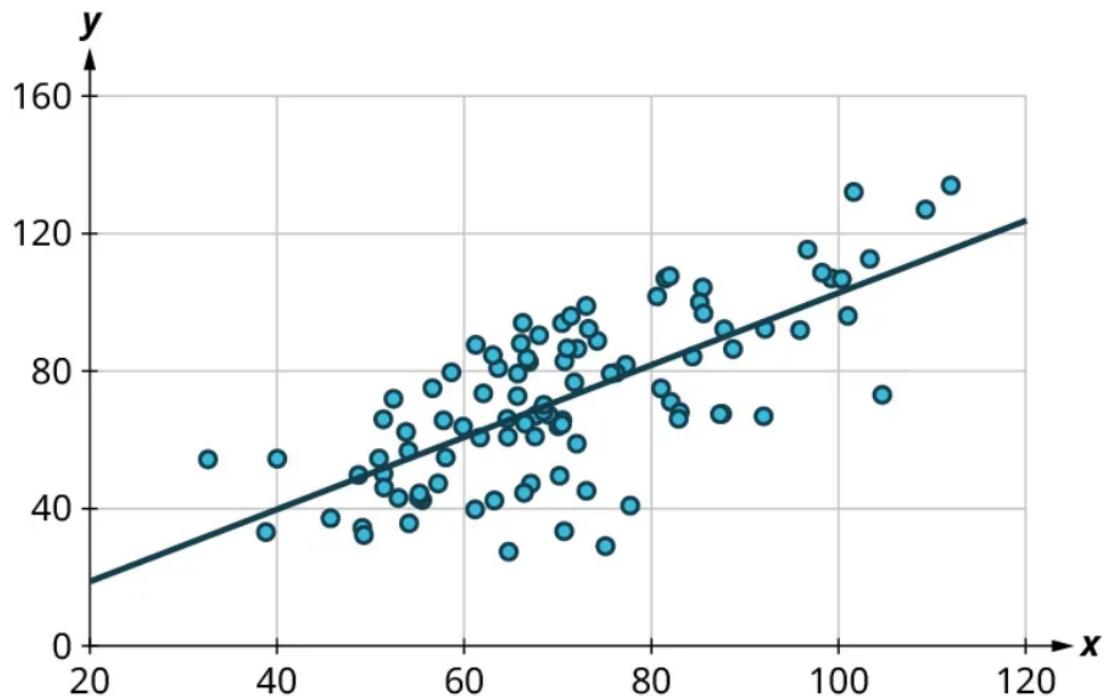
### **2.2.3 Linear Regression (LR)**

Linear Regression (LR) is a classical supervised learning method that models the relationship between a continuous response (e.g., yield or a parametric target) and one or more explanatory variables through a linear function. Owing to its computational simplicity and transparent parameterization, LR is frequently used in semiconductor manufacturing analytics as an interpretable baseline for yield prediction and process modeling, particularly when engineers require direct insight into how changes in key variables relate to expected quality outcomes (Adly et al., 2015; Chen & Toly, 2018).

Within yield prediction workflows, LR and related generalized linear models are commonly applied to (i) estimate continuous yield- or quality-linked targets from process and test measurements and (ii) provide fast, stable predictors that can be deployed for monitoring or as reference models in comparative evaluations. For example, (Chen & Toly, 2018) discusses linear-model-based approaches in virtual metrology settings where rapid inference is important, while (Adly et al., 2015) illustrates the use of regression-style models for relating process parameters to yield-relevant outcomes.

Despite its advantages, LR is constrained by its linearity assumption and limited capacity to represent complex interactions without feature transformations. Consequently, many studies position LR as a benchmark against which non-linear learners (e.g., SVMs and tree ensembles) are evaluated. In lithography-related prediction tasks, (Xu et al., 2018) compared linear regression baselines against more flexible models and reported that non-linear methods can achieve improved predictive performance and/or efficiency in practical workflows. Nevertheless, LR remains valuable when interpretability, computational efficiency, and ease of calibration are prioritized, and it is often strengthened by feature scaling, interaction terms, or dimensionality reduction in high-dimensional

manufacturing datasets (Chen & Toly, 2018; Xu et al., 2018).



**Figure 2.3. Conceptual illustration of linear regression, where a linear function is fitted to capture the relationship between an input variable and the target output.**

As shown in Figure 2.3, Linear Regression models the relationship between input features and the target variable by fitting a linear function, making it suitable for capturing direct and interpretable linear trends in semiconductor manufacturing data when linearity is a reasonable approximation.

#### 2.2.4 Extreme Gradient Boosting (XGBoost)

Extreme Gradient Boosting (XGBoost) is a gradient-boosted decision tree algorithm that builds an ensemble of weak learners in a stage-wise manner to minimize a regularized objective function. In semiconductor yield analytics, this regularization and the additive boosting formulation are attractive because they can capture non-linear feature

interactions while controlling overfitting, particularly in settings where process and test variables are numerous, noisy, and partially redundant.

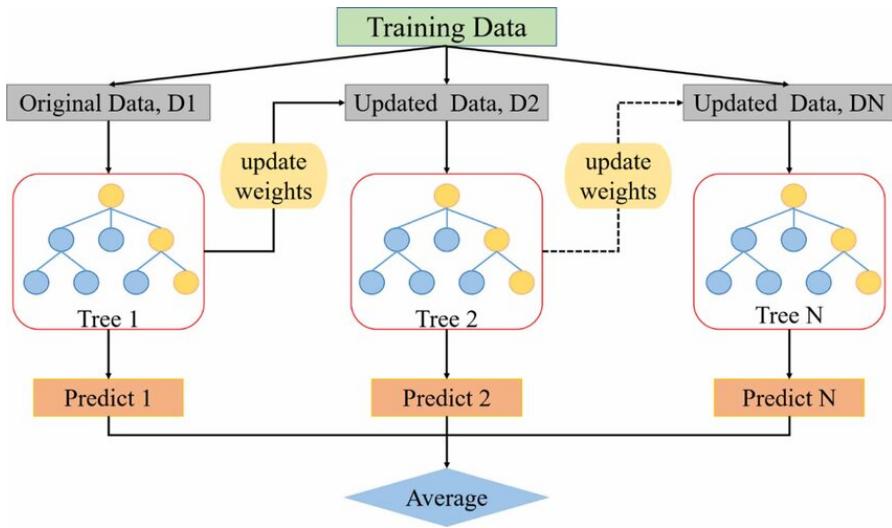
Within the proposed yield prediction workflow, XGBoost is typically positioned after pre-processing and feature engineering as a high-capacity predictive model for both classification and regression. Its tree-based structure accommodates mixed-type inputs and non-monotonic relationships between upstream measurements and downstream yield outcomes, while built-in importance scores provide an additional mechanism for ranking influential variables to support diagnosis and process improvement.

Recent semiconductor-oriented studies further motivate the inclusion of XGBoost in comparative benchmarking. (Shamsudin et al., 2023) proposed a cost-sensitive XGBoost approach optimized with Bayesian optimization for imbalanced semiconductor datasets, highlighting the practicality of boosting-based learners when yield-relevant classes are rare and misclassification costs are asymmetric. In virtual metrology applications, (Deivendran et al., 2025) reported that XGBoost, when evaluated alongside other traditional models, contributes competitive predictive performance for process outcome estimation, supporting its role as a strong baseline in yield prediction studies. Collectively, these findings indicate that XGBoost is a suitable candidate for benchmarking against SVM, Random Forest, and linear baselines when developing robust and deployable yield prediction models.

As shown in Figure 2.4, XGBoost employs a gradient boosting framework in which multiple decision trees are trained sequentially to correct the prediction errors of preceding models, enabling effective learning of complex non-linear relationships and feature interactions commonly present in high-dimensional semiconductor manufacturing data.

### 2.2.5 Decision Trees

Decision Trees (DTs) are non-parametric supervised learning models that perform classification or regression by recursively partitioning the feature space into regions defined by a sequence of decision rules. At each internal node, a split is selected to reduce an



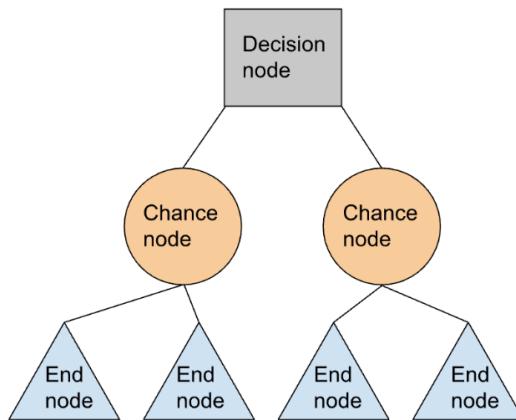
**Figure 2.4. Illustration of the XGBoost gradient boosting process where multiple decision trees are trained sequentially to correct prediction errors and model complex non-linear relationships (Friedman, J. H., 2001).**

impurity criterion (e.g., Gini index or entropy for classification, variance reduction for regression), and the resulting leaf nodes output either a class label (e.g., pass/fail or low-yield vs. normal-yield) or a continuous estimate of a yield-related target.

In semiconductor yield prediction workflows, DTs are commonly positioned as transparent baseline models for both final test yield classification and yield/quality regression tasks, because their rule-based structure can be inspected by process engineers to identify candidate thresholds and interactions among upstream variables. For example, machine-learning frameworks for semiconductor final test yield classification typically include tree-based learners among the benchmarked traditional algorithms, reflecting their practicality when fast training and interpretability are prioritized (Jiang et al., 2020). Similarly, yield prediction studies that integrate heterogeneous process and test information frequently use tree-structured models (either directly or as components within larger frameworks) to capture non-linear dependencies while retaining a degree of explainability (Jiang et al., 2021; Lee et al., 2023).

Despite these advantages, single decision trees are known to be sensitive to small data perturbations and can overfit without appropriate stopping rules or pruning, particularly

in high-dimensional settings common to manufacturing analytics. Consequently, DTs are often treated as a diagnostic or explainable reference point relative to more stable ensemble extensions (e.g., Random Forest or gradient boosting), while still offering a useful mechanism for summarizing complex multivariate relationships into actionable decision logic in yield-oriented applications (Deivendran et al., 2025; Maitra et al., 2024).



**Figure 2.5. Schematic illustration of a Decision Tree model, where internal nodes represent feature-based splitting rules and terminal leaves provide the predicted class or continuous output.**

As illustrated in Figure 2.5, the model routes each observation from the root node through a sequence of binary decision rules based on input features. At each split, the feature and threshold are selected to improve node purity (or reduce prediction error), and the traversal ends at a leaf node that outputs the final prediction. This structure provides an explicit, human-interpretable set of rules that can be examined to understand how different process and test variables contribute to yield-related decisions.

## 2.3 Feature Engineering in Semiconductor Yield Prediction and Analytics

Feature engineering is a central step in semiconductor yield prediction because raw manufacturing data are heterogeneous (equipment sensor traces, inline metrology, Wafer Acceptance Test (WAT), and Final Test (FT) measurements) and often contain noise, missing values, outliers, and drift. Consequently, the predictive quality and deployability of traditional machine learning models depend strongly on how these signals are cleaned, aligned, and transformed into stable feature representations. In particular, systematic preprocessing choices such as scaling, imputation, and outlier handling have been shown to materially influence downstream model performance in semiconductor process datasets (Park et al., 2024).

Beyond basic preprocessing, feature construction aims to encode process-relevant structure and reduce nuisance variability so that models can learn relationships that generalize across lots, tools, and operating conditions. In yield-oriented applications, this commonly includes aggregating high-frequency sensor readings into summary descriptors (e.g., windowed statistics), generating interaction features motivated by process knowledge, and deriving compact representations that emphasize condition changes linked to yield loss mechanisms. For example, clustering-based representations and ensemble modeling have been used to capture latent operating regimes in final test yield prediction, illustrating how engineered representations can improve the signal-to-noise ratio of yield predictors (Jiang et al., 2021; Maitra et al., 2024).

Because semiconductor datasets are frequently high-dimensional, feature selection and dimensionality reduction are also used to improve robustness, reduce overfitting risk, and lower inference cost. Recent work has proposed dimensionality reduction methods tailored to correlated sensor streams (e.g., sparse PCA variants) for virtual metrology, while other studies employ filter/embedded selection strategies (e.g., mutual information, L1 regularization, or Lasso-type selection) to retain only yield-informative variables (Deivendran et al., 2025; Shaer et al., 2023; Wang et al., 2024; Yeh et al., 2024). In ramp-up and yield improvement contexts, these feature engineering steps support faster learning cycles by stabilizing model training as process conditions evolve (Xu et

al., 2024).

### 2.3.1 Common Feature Types in Semiconductor Yield Analysis

Unlike studies that work with physically interpretable measurements (e.g., specific tool sensors or inline metrology channels), the SECOM dataset used in this study provides a fixed-length vector of anonymized variables indexed as  $F1-F590$ . Because the original feature semantics are not disclosed (a common constraint for industrial benchmark datasets), feature engineering in this work focuses on producing numerically stable and model-compatible representations that improve yield classification performance (Park et al., 2024).

In this setting, the most practically relevant “feature types” can be grouped as follows. Raw process and test variables correspond to the original indexed measurements and form the primary input space for the learning algorithms. Data-quality and missingness indicators (implemented as binary flags during preprocessing, where applicable) are often introduced to retain information about censored, unmeasured, or invalid readings; this is particularly important in high-dimensional manufacturing data where missing values are prevalent (Park et al., 2024). Finally, derived and transformed features are used to reduce redundancy and improve generalization, including standardized/scaled versions of the raw variables, low-dimensional representations obtained via dimensionality reduction, and subsets produced by feature selection methods that target correlated and noisy sensor streams (Deivendran et al., 2025; Shaer et al., 2023; Wang et al., 2024; Yeh et al., 2024). Collectively, these categories reflect common practice in semiconductor yield analytics, where robust preprocessing, selection, and compact representations are repeatedly shown to be critical for learning reliable yield predictors from large sets of heterogeneous manufacturing signals (Jiang et al., 2021; Maitra et al., 2024).

### **2.3.2 Feature Selection Approaches in Semiconductor Yield Analysis**

Feature selection is frequently required in semiconductor yield analysis because process datasets are high-dimensional, noisy, and strongly correlated, which can degrade generalization and inflate model complexity. Accordingly, yield modeling studies commonly combine preprocessing with selection strategies that either explicitly search for informative subsets or encourage sparsity during training (Park et al., 2024; Wang et al., 2024; Yeh et al., 2024).

Wrapper methods evaluate candidate feature subsets by repeatedly fitting a predictive model and selecting the subset that optimizes a validation criterion. In yield classification, this includes strategies such as forward selection, backward elimination, and recursive feature elimination (RFE), which can be paired with classifiers like SVMs or tree ensembles to identify compact subsets of the anonymized SECOM variables that maximize discriminative performance while controlling overfitting (Yeh et al., 2024).

Embedded methods perform selection as part of model training. Regularization-based approaches (e.g., L1-type penalties) promote sparse solutions by shrinking weak predictors toward zero, while tree-based learners implicitly rank variables through split gains and impurity reductions. These embedded mechanisms are attractive in manufacturing analytics because they scale to large feature spaces and provide an operational notion of importance that can be used for model compression and subsequent diagnosis (Deivendran et al., 2025; Shaer et al., 2023).

Although many studies apply feature selection within a single modeling pipeline, there remains a practical need for more systematic evaluation of how different selection strategies interact with preprocessing choices, class imbalance handling, and downstream learners when developing robust yield prediction systems (Maitra et al., 2024; Park et al., 2024).

## 2.4 Dataset Diversity and Model Generalizability

A persistent challenge in semiconductor yield analysis is that datasets collected across different fabs, tools, product variants, and time periods can exhibit substantial heterogeneity. Even when the prediction target is defined consistently (e.g., yield loss, low-yield screening, or quality pass/fail), changes in equipment configurations, sensor calibration, sampling rates, and process recipes can shift the underlying data distribution and alter which variables are informative. As a result, models trained on a single operating regime may achieve high in-sample accuracy yet generalize poorly when deployed under new production conditions or during ramp-up, where drift and regime changes are common (Jiang et al., 2021; Q. Wang & Huang, 2025; Xu et al., 2024).

A second source of limited generalizability arises from differences in data representation and labeling. Public benchmark datasets such as SECOM provide high-dimensional process measurements with anonymized feature indices ( $F1$ – $F590$ ), which supports reproducible comparisons but limits domain interpretability and can constrain transfer to settings where sensors and measurement definitions differ. In addition, manufacturing datasets frequently contain missing values, noisy readings, and class imbalance, which can bias learned decision boundaries and make reported performance sensitive to preprocessing, resampling, and evaluation design (Park et al., 2024).

To improve reliability, prior work emphasizes evaluation protocols and modeling choices that explicitly account for heterogeneity. Consistent cross-validation and repeated-split experiments provide more stable estimates than single holdout tests, while feature selection and regularization can reduce sensitivity to spurious correlations in high-dimensional inputs (Shaer et al., 2023; Wang et al., 2024; Yeh et al., 2024). Nevertheless, the literature continues to report that transferring models across datasets or production contexts often requires retraining and/or additional feature engineering to maintain accuracy, highlighting the need for broader benchmarking across multiple datasets and operating regimes (L. Chen & Zhang, 2024; Park et al., 2024; Xu, Hong-Wei, et al., 2022).

## **2.5 Comparative Studies and Benchmarking in Machine Learning for Semiconductor Yield Prediction**

Comparative studies and benchmarking have been instrumental in establishing practical baselines for semiconductor yield prediction, particularly when multiple conventional learners (e.g., SVM, tree ensembles, and linear models) are evaluated under manufacturing constraints such as high dimensionality, missing values, and class imbalance (Jiang et al., 2021; Park et al., 2024). However, the yield analytics literature also exhibits recurring methodological inconsistencies that complicate direct cross-study comparison and can lead to over-optimistic conclusions.

One common issue is limited comparability across datasets and evaluation splits. Studies frequently report results on different data sources (often proprietary) or under non-uniform train/test protocols, making it difficult to attribute performance differences to algorithms rather than to dataset characteristics or sampling decisions (L. Chen & Zhang, 2024; Xu, Hong-Wei, et al., 2022). A second inconsistency concerns evaluation metrics. Because yield-related classification problems are often imbalanced, accuracy alone can be misleading; nevertheless, reported metrics vary widely across studies, and the choice of metric can materially change which model appears superior (Park et al., 2024).

A further concern is that many comparisons implicitly assume a fixed feature representation, even though model performance can be highly sensitive to preprocessing (scaling, imputation, outlier handling), resampling strategies, and feature selection choices. For example, optimization-driven pipelines and imbalance-aware preprocessing have been shown to materially influence yield screening performance on benchmark manufacturing datasets, suggesting that “algorithm comparisons” should be interpreted jointly with the feature engineering and data preparation steps used to produce model inputs (Dash et al., 2024; Park et al., 2024; Yeh et al., 2024).

Overall, the absence of standardized benchmarking protocols that simultaneously control (i) dataset and split design, (ii) metric selection for imbalanced outcomes, and (iii) feature–algorithm pairings remains a key gap. Addressing this gap requires broader, more reproducible evaluations across diverse operating regimes and consistent experi-

mental designs that support reliable conclusions about model robustness and deployability (L. Chen & Zhang, 2024; Jiang et al., 2021; Xu, Hong-Wei, et al., 2022).

**Table 2.1. Comparative Studies and Benchmarking of Traditional Machine Learning in Semiconductor Yield Prediction**

No.	Study	Algorithms Compared	Best Performing Algorithm(s)	Performance Highlights
1	(Chen et al., 2023)	ECOC with SVM vs. traditional classifiers	Support Vector Machine (SVM)	Achieved 96.96% accuracy on wafer defect classification
2	(Behera et al., 2024)	Bayesian-optimized SVM vs. baseline SVM	Optimized SVM	Accuracy improved from 74.5% to 88.1% post optimization
3	(Xu et al., 2018)	SVM vs. Logistic Regression (LGR)	Support Vector Machine (SVM)	Achieved comparable accuracy but with >3x computational speedup for SRAF generation
4	(Deivendran et al., 2025)	Lasso Regression, Random Forest, XG-Boost	Random Forest, XG-Boost	Improved CMP yield prediction accuracy with hybrid ensemble framework
5	(Dash et al., 2024)	Bayesian Optimization with SVM vs. non-optimized models	Optimized SVM	Achieved consistently high predictive performance for defect detection
6	(Park et al., 2024)	ADASYN, MaxAbs Scaling with SVM vs. baseline models	SVM with Preprocessing	Achieved 85.14% accuracy, 72.95% geometric mean on SECOM dataset
7	(Shaer et al., 2023)	Standard SVM vs. L1-Regularized SVM	L1-Regularized SVM	Achieved 179x computational speedup in defect detection workflows

### 2.5.1 Analysis of Traditional Machine Learning Approaches

Table 2.1 synthesizes representative comparative studies that apply traditional machine learning to semiconductor quality prediction problems, including yield screening, virtual metrology, and closely related defect/quality classification tasks. Across these works, performance is driven not only by the choice of learner (e.g., SVMs and tree ensembles) but also by how high-dimensional process and test measurements are preprocessed and reduced to stable feature representations (Park et al., 2024; Yeh et al., 2024).

A consistent finding is that margin-based classifiers and ensembles provide strong baselines in high-dimensional settings. For instance, SVM-centered pipelines report competitive accuracy in multiple contexts, and improvements are often obtained by coupling SVMs with optimization or carefully chosen preprocessing steps (Behera et al., 2024; Chen et al., 2023; Park et al., 2024). Tree-ensemble approaches (Random Forest and gradient-boosted trees such as XGBoost) are similarly prominent because they capture non-linear interactions and yield practical importance rankings that support diagnosis and process improvement (Deivendran et al., 2025).

The table also highlights that reported gains frequently depend on the experimental protocol and operational constraints rather than algorithm choice alone. In particular, computational efficiency can be a first-order consideration in manufacturing analytics: Xu et al. (2018) showed that SVM-based solutions can match baseline predictive quality while substantially reducing runtime, which is crucial for high-throughput simulation and decision support. Likewise, sparsity-inducing formulations (e.g., L1-regularized SVMs) can reduce effective dimensionality and accelerate analysis, reinforcing the value of embedded selection mechanisms in scalable yield workflows (Shaer et al., 2023).

Overall, the comparative evidence suggests that traditional models remain competitive for yield prediction when the pipeline is designed holistically—that is, when feature selection, imbalance handling, scaling/imputation, and evaluation metrics are aligned with the deployment objective. This motivates the present study’s emphasis on controlled benchmarking under consistent preprocessing and validation settings on the SECOM dataset (Park et al., 2024).

## CHAPTER 3

### METHODOLOGY

This chapter presents the complete technical methodology adopted to develop and evaluate a semiconductor yield prediction framework using the SECOM dataset. The proposed framework is organized as a structured machine learning pipeline that transforms high-dimensional manufacturing measurements into robust predictors by combining data preprocessing, feature selection, and comparative model training. A central design principle of this study is the strict prevention of data leakage. To ensure reliable and unbiased performance evaluation, the test data are fully isolated from all preprocessing, class-imbalance handling, and feature selection procedures by fitting these operations only on the training portion within each validation split. Consequently, the reported results reflect model generalization to previously unseen manufacturing samples (Jiang et al., 2021; Park et al., 2024).

#### 3.1 Overall Pipeline Structure

The proposed yield prediction workflow is implemented as a Directed Acyclic Graph (DAG) of sequential, non-overlapping stages to enforce a strict forward data flow and to minimize opportunities for information leakage between training and evaluation steps. This design choice is particularly important for high-dimensional semiconductor process datasets, where preprocessing decisions (e.g., imputation and scaling) and dimensionality reduction can otherwise inadvertently encode information from held-out samples (Park et al., 2024).

The pipeline consists of six stages. First, the SECOM records are ingested and cleaned by removing invalid entries and applying missing-value handling appropriate for sensor-derived manufacturing data. Second, the dataset is partitioned into training and test

splits (and, where applicable, cross-validation folds) to establish a fixed evaluation boundary. Third, training-only preprocessing is performed, including feature scaling and class-imbalance handling, reflecting common practice in yield screening problems where defective outcomes are rare (Park et al., 2024). Fourth, feature selection is applied to reduce redundancy and improve robustness by retaining a compact subset of the anonymized variables through recursive elimination and/or sparsity-inducing learning formulations (Shaer et al., 2023; Yeh et al., 2024). Fifth, multiple traditional classifiers are trained and tuned under consistent hyperparameter optimization settings to support fair comparison across model families (Dash et al., 2024). Finally, the tuned models are evaluated on held-out data using metrics suitable for imbalanced classification.

### 3.2 Data Ingestion and Initial Cleaning

The pipeline begins by loading the SECOM semiconductor manufacturing dataset, which provides anonymized, high-dimensional process and test measurements together with a binary yield-related label for each production instance. Because such manufacturing data are typically collected from heterogeneous sensors under real production variability, the raw records often contain missing values, noise, and inconsistencies that must be addressed prior to model training (Jiang et al., 2021; Park et al., 2024).

During ingestion, the feature matrix and labels are aligned to ensure one-to-one correspondence between samples and targets, and non-predictive identifiers (e.g., timestamps or logging fields) are excluded from the learning input to prevent spurious correlations. Initial cleaning then removes malformed records and applies systematic handling of missing values, following preprocessing practices shown to materially affect downstream yield classification performance on SECOM-like datasets (Park et al., 2024). Finally, basic screening is performed to identify trivially uninformative variables (e.g., near-constant features) and extreme outliers indicative of sensor faults, improving numerical stability before subsequent scaling, imbalance handling, and feature selection steps (Kim, Eunji, et al., 2023).

### **3.3 Data Splitting and Hybrid Balancing**

After initial cleaning, the dataset is divided into a training partition and a locked hold-out test partition. The split is performed in a stratified manner to preserve the class distribution between partitions, which is important for yield screening tasks where the minority (fail) class can be relatively rare. The hold-out test set is isolated prior to any data-dependent transformations so that preprocessing, feature expansion, and selection are learned strictly from the training data, thereby reducing the risk of optimistic bias due to leakage.

Because SECOM exhibits class imbalance, hybrid balancing is applied exclusively to the training data. In practice, this step combines controlled reduction of the majority class with synthetic or resampling-based enrichment of the minority class, aiming to improve sensitivity to rare fail cases without distorting the evaluation distribution. Such resampling strategies have been reported as consequential for traditional yield classifiers on SECOM, particularly when coupled with appropriate scaling and model selection (Park et al., 2024).

#### **3.3.1 Implementation details for leakage prevention**

To operationalize the no-leakage principle, the pipeline is implemented such that every data-dependent transformation is learned from training data only and then applied to validation/test data using the learned parameters. Concretely, for each train/validation split produced during cross-validation, the following sequence is executed:

1. Split the data into training fold and validation fold using stratification.
2. Fit imputation and scaling parameters on the training fold only; transform both the training and validation folds using these fitted parameters.
3. Apply imbalance handling on the training fold only.
4. Fit feature selection on the training fold only; transform both folds to the selected feature space.
5. Fit the classifier on the transformed training fold and evaluate on the transformed

validation fold.

After model selection, the final pipeline is refit on the full training partition (using the same ordering) and evaluated exactly once on the locked hold-out test set. This design prevents information from the validation or test partitions from influencing preprocessing, feature selection, or model tuning decisions (Dash et al., 2024; Park et al., 2024).

### 3.4 Feature Extraction Framework

In contrast to image-based defect analysis, the SECOM dataset provides each instance as a fixed-length vector of anonymized manufacturing variables ( $F1$ – $F590$ ). Accordingly, “feature extraction” in this study focuses on constructing a numerically stable and information-preserving representation from the raw sensor and test measurements rather than computing handcrafted spatial descriptors. This choice is consistent with yield analytics practice, where the dominant performance drivers are data quality handling, scaling, and dimensionality reduction in high-dimensional, partially missing process data (Jiang et al., 2021; Park et al., 2024).

The feature representation is organized into three complementary groups. First, base process/test variables correspond to the original indexed measurements and form the core input space for all models. Second, preprocessing-derived features include standardized versions of the variables and, where missingness is present, indicator flags that preserve information about censored or invalid readings while enabling consistent downstream modeling (Park et al., 2024). Third, compressed/selected representations are produced through feature selection or dimensionality reduction to mitigate multicollinearity and noise, and to reduce effective model complexity; such representations are widely reported as beneficial for robust learning in semiconductor manufacturing datasets (Shaer et al., 2023; Wang et al., 2024; Yeh et al., 2024).

This representation framework is designed to support fair benchmarking across traditional learners by providing consistent inputs while allowing the contribution of selection and transformation steps to be evaluated explicitly as part of the end-to-end yield pre-

diction pipeline (Maitra et al., 2024).

### 3.5 Feature Expansion and Selection

After establishing a consistent base representation for each SECOM instance, the pipeline optionally enriches the input space to better capture non-linear effects and interaction mechanisms among process variables, and then applies feature selection to control dimensionality and reduce sensitivity to noise (Park et al., 2024).

#### 3.5.1 Feature Expansion

To represent non-linear effects and cross-variable coupling among process measurements, a second-degree polynomial feature expansion can be applied to the standardized inputs. This transformation augments the original variables with interaction terms (e.g.,  $F_i F_j$ ) and squared terms (e.g.,  $F_i^2$ ), which can increase the expressiveness of linear learners when relationships between process settings and yield outcomes are not well captured by purely additive effects. Because polynomial expansion can rapidly increase dimensionality in high-dimensional manufacturing data, it is treated as an optional, training-only transformation and is paired with subsequent feature selection or sparsity-inducing modeling choices to control complexity and reduce overfitting risk (Park et al., 2024; Shaer et al., 2023).

#### 3.5.2 Feature Selection Strategy

To mitigate overfitting and reduce computational cost in the high-dimensional SECOM setting, feature selection is performed as a training-only step within each validation split. This choice reflects a recurring theme in yield analytics: many manufacturing variables are redundant or weakly informative, and compact feature subsets can improve both robustness and efficiency in downstream learning (Wang et al., 2024).

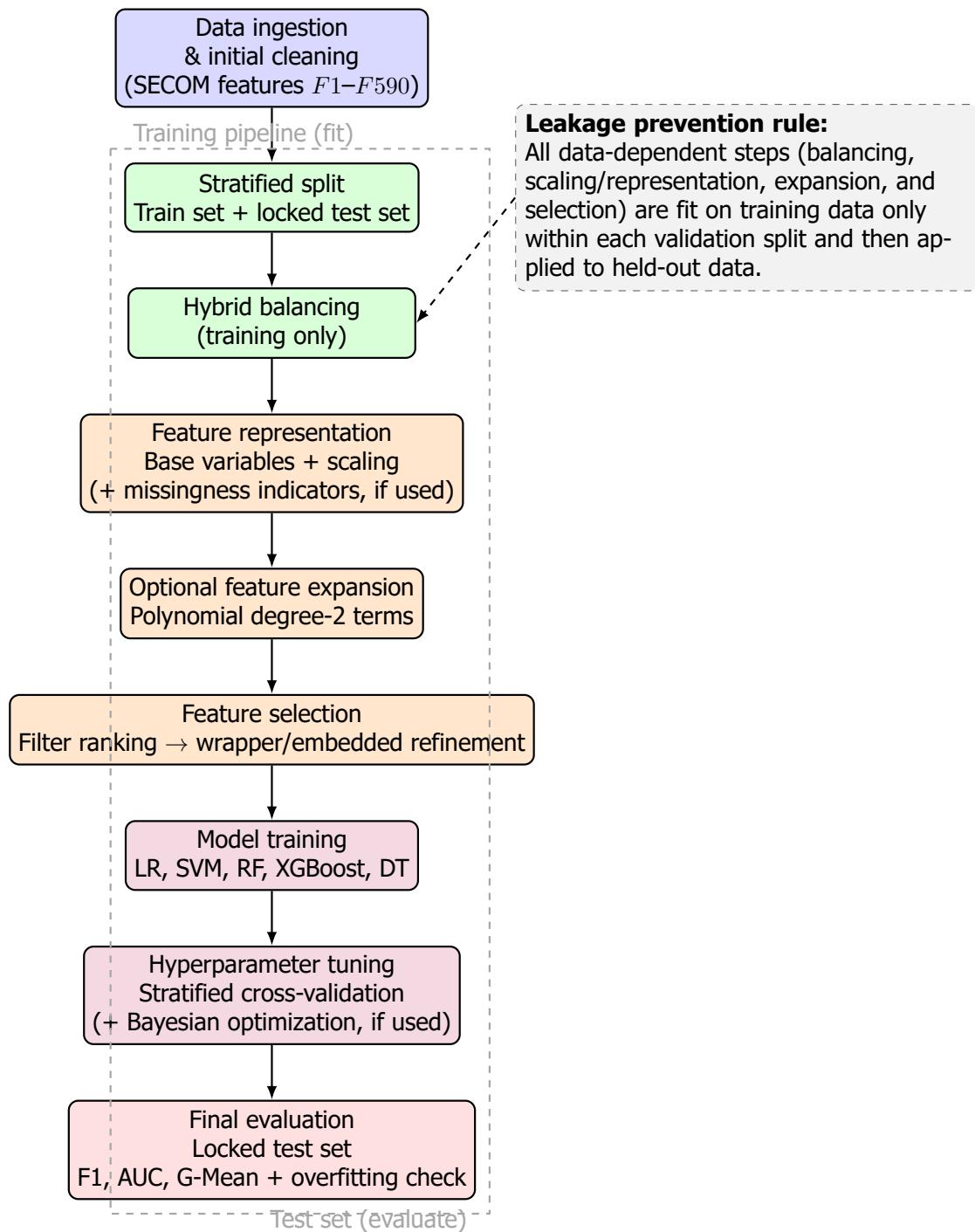
A two-stage approach is adopted. First, a lightweight filter stage ranks features using univariate relevance criteria computed on the training data (e.g., mutual-information-based scoring) and discards variables with minimal association to the class label. Such filter-based screening provides a scalable first reduction in uneven, high-dimensional settings and can stabilize subsequent model fitting (Xu, Qiuhan, et al., 2022; Yeh et al., 2024).

Second, a wrapper/embedded refinement stage further compresses the feature set using model-driven selection (e.g., recursive elimination using a linear estimator or sparsity-inducing formulations). By incorporating the learner’s sensitivity to correlated inputs, this refinement step can yield a compact subset that supports faster training and more interpretable analysis of influential variables (Shaer et al., 2023).

### 3.6 Model Training and Evaluation

Using the selected feature representation, multiple traditional classifiers are trained to benchmark predictive performance for SECOM yield screening. The model set includes linear baselines (e.g., Logistic Regression), margin-based learners (SVM), and tree-based ensembles (Random Forest and gradient-boosted trees such as XGBoost), reflecting algorithm families that are frequently reported as competitive on semiconductor manufacturing data (Deivendran et al., 2025; Park et al., 2024; Yeh et al., 2024).

Hyperparameters are tuned on the training data using stratified cross-validation to preserve the imbalanced class distribution in each fold. Where applicable, Bayesian optimization is employed to search the hyperparameter space efficiently under a consistent validation protocol, supporting fair comparison across model families (Dash et al., 2024). Final performance is reported on the locked hold-out test set using metrics suitable for imbalanced yield outcomes, with emphasis on F1-score and complementary measures such as AUC and geometric mean when appropriate. Overfitting is assessed by comparing cross-validated training performance against held-out test performance and by inspecting the stability of results across folds (Park et al., 2024).



**Figure 3.1. Summary flowchart of the proposed end-to-end methodology for SECOM-based semiconductor yield prediction, highlighting the sequential pipeline stages and the training-only constraint used to prevent data leakage.**

# CHAPTER 4

## RESULTS AND DISCUSSION

### 4.1 Overview

This chapter presents the empirical findings obtained from implementing the automated machine learning pipeline introduced in Chapter 3 for semiconductor yield prediction using the SECOM dataset. The experimental evaluation validates the proposed leak-proof pipeline design and addresses the three study objectives defined in Section 1.7 by reporting results exclusively from the locked, independent test partition, thereby reflecting true generalization performance rather than optimistic estimates arising from inadvertent information leakage during preprocessing, balancing, or feature selection (Kim, Eunji, et al., 2023; Park et al., 2024).

The presentation is organized to mirror the sequential stages of the methodology, providing a coherent narrative from feature representation to final model verification. Section 4.2 addresses the first objective by identifying an effective feature set for semiconductor yield prediction. Specifically, it evaluates the feature engineering and selection strategies in the pipeline and quantifies the contribution of the Feature Combination stage, determining whether the reduction from a high-dimensional interaction space to a compact subset improves model convergence and stability while preserving discriminative information relevant to yield outcomes (Shaer et al., 2023; Yeh et al., 2024).

Section 4.3 fulfills the second objective by benchmarking the predictive performance of the seven traditional machine learning algorithms configured during the Model Tuning stage, including Support Vector Machines (SVM), Random Forests, and Gradient Boosting. This comparative analysis identifies the most suitable algorithmic paradigm for yield screening under class imbalance, and discusses trade-offs between computational cost, interpretability, and classification effectiveness on high-dimensional manufacturing measurements (Jiang et al., 2021; Park et al., 2024).

Finally, Section 4.4 addresses the third objective by assessing robustness and generalizability on unseen production data using the Overfit Gap metric and other test-set evaluation measures. This analysis directly validates the data partitioning strategy established during preprocessing and confirms whether the trained models maintain reliable performance when deployed beyond the data used for model selection (Park et al., 2024).

Collectively, the chapter not only reports experimental outcomes but also interprets the observed behaviors in relation to yield-relevant feature representations and model generalization. This dual emphasis ensures that the results are evaluated not only in terms of numerical performance, but also with respect to their physical plausibility and suitability for deployment in semiconductor manufacturing environments.

## 4.2 Feature selection Analysis (Objective 1)

As a prerequisite to meaningful model benchmarking, this section addresses Objective 1 by determining a compact and informative feature subset for semiconductor yield prediction on the SECOM dataset. Although the raw SECOM variables already constitute a high-dimensional sensor-derived measurement space, the optional Feature Combination stage further augments this representation by introducing second-degree interaction and squared terms. Such expansions can increase model expressiveness, but they also amplify multicollinearity, computational cost, and overfitting risk when many generated terms are redundant or weakly associated with the yield label (Kim, Eunji, et al., 2023; Park et al., 2024).

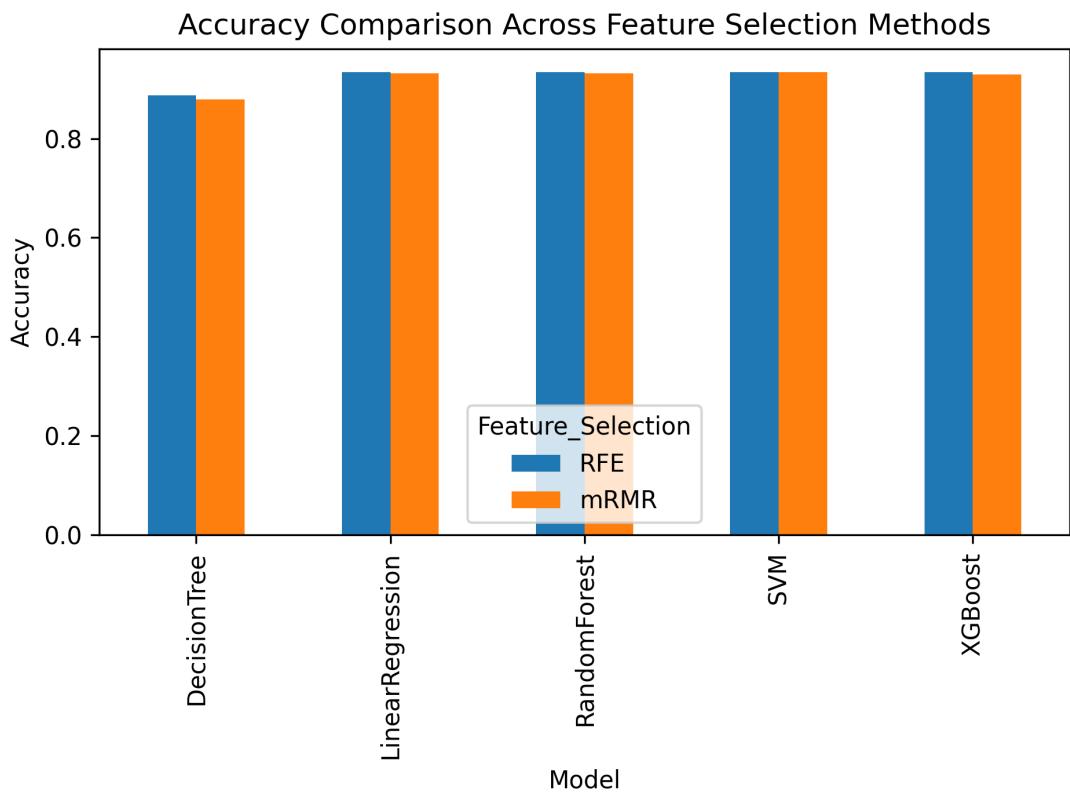
Accordingly, feature selection is treated as a critical bridge between feature engineering and classifier training. In semiconductor analytics, selecting a small subset of stable predictors is widely used to improve numerical stability, reduce sensitivity to noise and missingness patterns, and support more interpretable screening models (Shaer et al., 2023; Yeh et al., 2024). To preserve the integrity of the evaluation, all selection operations were performed strictly within the training portion of each validation split and then

applied to the corresponding validation/test data, ensuring that no information from unseen samples influenced the selected feature set (Park et al., 2024).

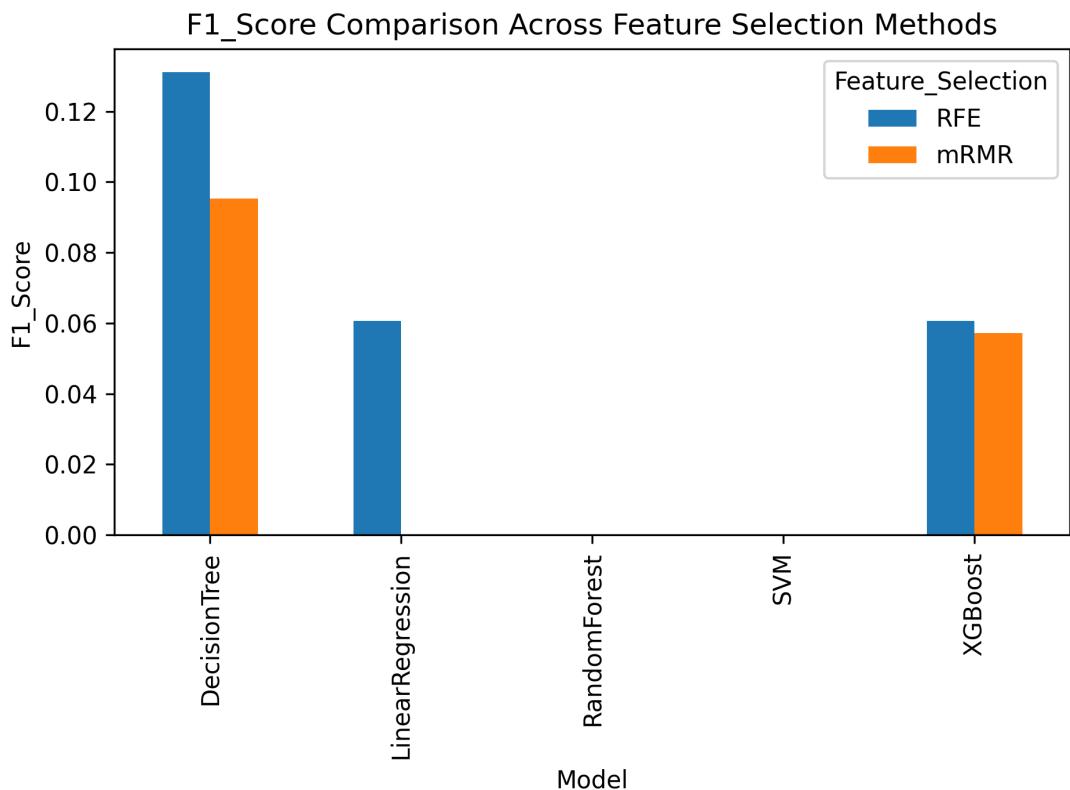
To identify an appropriate selection mechanism for SECOM, two feature selection methods were evaluated under identical preprocessing and data-partitioning conditions: Recursive Feature Elimination (RFE) as a wrapper-based approach, and minimum Redundancy–Maximum Relevance (mRMR) as a filter-based ranking approach. This pairing supports a focused comparison between (i) model-driven elimination based on predictive contribution and (ii) relevance/redundancy ranking computed prior to model fitting, both of which have been used to improve robustness in high-dimensional semiconductor data (Shaer et al., 2023; Yeh et al., 2024).

#### **4.2.1 Feature selection methods and subset sizing**

This subsection summarizes the two feature selection methods and the logic used to determine the number of retained variables. Because SECOM yield prediction is class-imbalanced and contains many correlated sensor measurements, the choice of subset size influences not only computational efficiency, but also the stability of model training and the reliability of test-set generalization (Kim, Eunji, et al., 2023; Park et al., 2024). Across the evaluated classifiers, both RFE and mRMR produced broadly similar accuracy values (Figure 4.1). However, accuracy alone is not a sufficient indicator of screening quality in SECOM-style settings, because a model can achieve high accuracy by predominantly predicting the majority (non-failure) class. This effect is reflected by the markedly low F1-scores in Figure 4.2, indicating that the minority (failure) class remains difficult to identify despite apparently strong overall accuracy (Jiang et al., 2021; Park et al., 2024).



**Figure 4.1. Accuracy comparison across feature selection methods.**



**Figure 4.2. F1-score comparison across feature selection methods.**

**Table 4.1. Comparison of evaluated feature selection methods and subset sizing logic. The table distinguishes between each method's selection mechanism and how the final feature count was determined.**

Method	Category	Mechanism & sizing logic	Count
Recursive Feature Elimination (RFE)	Wrapper	Mechanism: iteratively fits a base estimator and removes the least informative variables until the target subset size is reached. Sizing logic: fixed at 50 based on training-only validation, selecting a compact subset beyond which accuracy improvements were marginal and F1-score did not improve consistently.	50
mRMR	Filter	Mechanism: ranks variables to maximize relevance to the yield label while minimizing redundancy among selected variables. Sizing logic: fixed at 50 to match RFE, enabling a controlled comparison where the selection mechanism (wrapper versus filter ranking) is the primary difference.	50
Lasso (L1 regularization)	Embedded	Mechanism: enforces sparsity by shrinking coefficients toward zero via an L1 penalty. Sizing logic: automatic; under the evaluated settings, all coefficients were shrunk to zero, yielding an empty selected set.	0

#### 4.2.2 Comparative results

The effectiveness of the evaluated feature selection strategies was assessed by training the downstream classifiers on each selected subset and comparing performance on the locked test partition. Although test-set accuracy is reported for completeness, the primary metric for comparison is the Macro F1-score, which is more appropriate for SECOM yield screening because it weights the minority (failure) and majority classes equally and is therefore less sensitive to class prevalence (Jiang et al., 2021; Park et al., 2024).

Table 4.2 summarizes the comparative outcomes. Overall, the two 50-feature subsets

produced similar accuracy across most classifiers, consistent with Figure 4.1. However, the Macro F1-score provides a more discriminative view of practical utility, revealing whether the retained variables support meaningful identification of rare yield failures rather than simply preserving majority-class correctness.

**Table 4.2. Comparative analysis of feature selection strategies based on test-set Macro F1-score (primary metric) and accuracy (secondary metric). “Best model” denotes the classifier with the highest Macro F1-score under each feature selection method.**

Selection method	Count	Best model	Accuracy	Macro F1
RFE (wrapper)	50	Decision Tree	0.8875	0.1311
mRMR (filter)	50	Decision Tree	0.8790	0.0952

In interpreting Table 4.2, RFE yields the stronger screening performance, achieving a higher Macro F1-score than mRMR at the same dimensionality. Notably, several model configurations attain high accuracy (approximately 0.93) while producing near-zero F1-score, which is consistent with majority-class prediction in an imbalanced yield setting. The improvement in Macro F1 under RFE suggests that model-aware elimination can better prioritize variables that contribute to minority-class separation in the correlated SECOM feature space (Park et al., 2024; Shaer et al., 2023; Yeh et al., 2024).

Based on these results, **RFE was selected as the preferred feature selection strategy** and is adopted for the subsequent model performance evaluation in Section 4.3. More broadly, the comparison indicates that yield-screening performance is driven primarily by the relevance and stability of the retained variables rather than by feature count alone: despite identical dimensionality (50 features), RFE provided a more informative representation for detecting rare failure outcomes, whereas alternative rankings were more susceptible to redundancy in the high-dimensional SECOM measurement space (Park et al., 2024; Yeh et al., 2024).

The Lasso configuration is not included in the comparative table because it selected zero features under the evaluated settings, and therefore did not produce a usable representation for downstream classification.

#### **4.2.3 Study-by-study feature comparison with prior SECOM work**

To contextualize the engineered feature representation used in this project, Table 4.3 provides a study-by-study comparison showing how feature sets reported in prior SECOM dataset-based studies correspond to, or are extended by, the overlapping and interaction-based features considered here. Because SECOM variables are anonymized, the comparison is presented at the level of feature types (e.g., raw sensor variables, filtered top- $k$  subsets, and interaction terms) rather than specific process-variable semantics.

**Table 4.3. Study-by-study feature comparison illustrating how feature representations proposed in prior SECOM-related work correspond to, or are extended by, the base, interaction, and selected feature spaces used in this project.**

Reference	Feature(s) defined in literature	Corresponding/enhanced feature(s) in this study
(Yeh et al., 2024)	Feature selection for semiconductor classification using optimization-based search to identify compact, discriminative subsets from high-dimensional measurements.	Alternative selection mechanisms (wrapper RFE and filter mRMR) evaluated under identical preprocessing; selection applied after optional second-degree interaction expansion to control dimensionality while preserving discriminative signal.
(Wang et al., 2024)	Dimensionality reduction for sensor data in semiconductor virtual metrology using sparse/structured representations to improve efficiency and robustness.	Dimensionality is controlled through feature selection (50-variable subsets) rather than projection; additionally, interaction features ( $x_i x_j$ ) are generated only when paired with selection to mitigate overfitting risk in high-dimensional sensor spaces.
(Kim, Eunji, et al., 2023)	Sensor data mining for low-yield diagnosis, emphasizing that a small subset of variables often carries actionable signal while many measurements are redundant or weakly informative.	The adopted RFE subset provides a compact representation intended to retain the most yield-informative SECOM variables while reducing redundancy; the interaction expansion is used to capture cross-variable coupling where supported by feature selection.

### **4.3 Performance of Traditional Machine Learning Algorithms (Objective 2)**

Having established Recursive Feature Elimination (RFE) as the preferred feature selection strategy in Section 4.2, the analysis now shifts from feature-level optimization to model-level performance evaluation. This section examines how different traditional machine learning algorithms respond to the fixed 50-feature RFE representation and whether variations in model complexity translate into improved yield-screening performance on previously unseen SECOM test samples. By benchmarking a diverse set of classifiers under a unified, leak-proof experimental framework, the aim is to identify not only the model with the highest overall accuracy, but also the model that provides the most balanced and generalizable performance under class imbalance, as reflected by Macro F1-score (Jiang et al., 2021; Park et al., 2024).

By holding the feature representation constant (RFE, 50 features), this analysis isolates algorithmic behavior as the primary experimental variable. This controlled design enables a direct assessment of how inductive bias and model capacity influence minority-class detection and generalization when trained on the same data partitions and evaluated using identical metrics.

#### **4.3.1 Performance leaderboard**

To synthesize the comparative results, Table 4.4 consolidates the evaluation metrics into a final leaderboard based exclusively on the locked SECOM test set using the RFE 50-feature representation. The ranking is intended to jointly reflect overall classification correctness (accuracy) and balanced minority/majority performance (Macro F1-score), thereby making explicit the trade-off between raw predictive accuracy and class-wise reliability in an imbalanced yield-screening context (Jiang et al., 2021; Park et al., 2024). In addition, the Overfit Gap is reported as an indicator of generalization stability, computed here as the difference between training and test accuracy (

$$\text{Gap} = \text{Acc}_{train} - \text{Acc}_{test}$$

) under identical preprocessing and feature conditions. Smaller gaps indicate more stable generalization, whereas larger gaps suggest overfitting to the training distribution (Park et al., 2024).

**Table 4.4. Final model rankings using RFE-selected features (50 variables), sorted by test accuracy (tie-broken by Macro F1-score). Values are reported from the locked test set.**

Rank	Model	Accuracy (%)	Macro F1	Overfit Gap
1	XGBoost	93.42	0.0606	0.066 (High)
2	Linear Regression	93.42	0.0606	0.000 (Excellent)
3	SVM	93.42	0.0000	0.001 (Excellent)
4	Random Forest	93.42	0.0000	0.066 (High)
5	Decision Tree	88.75	0.1311	0.113 (Very High)

### 4.3.2 Performance of Linear Models (SVM and Linear Regression)

This subsection analyzes the behavior of the two linear model families evaluated under the fixed RFE 50-feature representation: Support Vector Machine (linear decision function) and Linear Regression used as a linear classifier. Both models achieved the highest test accuracy (93.42%), and both exhibited negligible accuracy gap (0.001 and 0.000, respectively), indicating stable generalization with respect to overall correctness. However, their Macro F1-scores were low (0.0000 for SVM and 0.0606 for Linear Regression), which indicates weak minority-class detection despite strong aggregate accuracy.

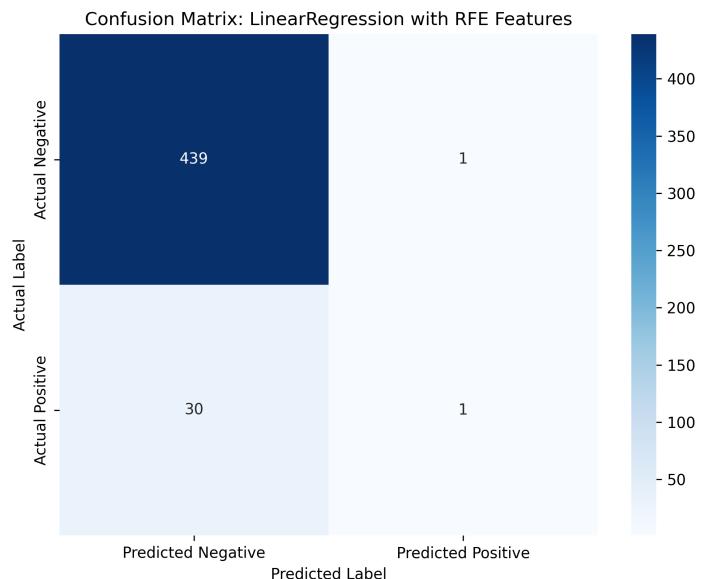
The SVM confusion matrix indicates very strong performance on the majority (non-failure) class ( $TN = 439$ ,  $FP = 1$ ), which explains the high overall accuracy. However, minority-class detection is poor ( $FN = 30$ ,  $TP = 1$ ), implying that the learned decision boundary largely prioritizes avoiding false alarms at the cost of missing rare yield failures. In an imbalanced screening context, this behavior is undesirable when the operational objective is early identification of failure cases; therefore, the Macro F1-score provides

a more realistic indicator of practical utility than accuracy alone (Jiang et al., 2021; Park et al., 2024).

**Table 4.5. SVM confusion matrix on the locked SECOM test set using RFE-selected features (50 variables).**

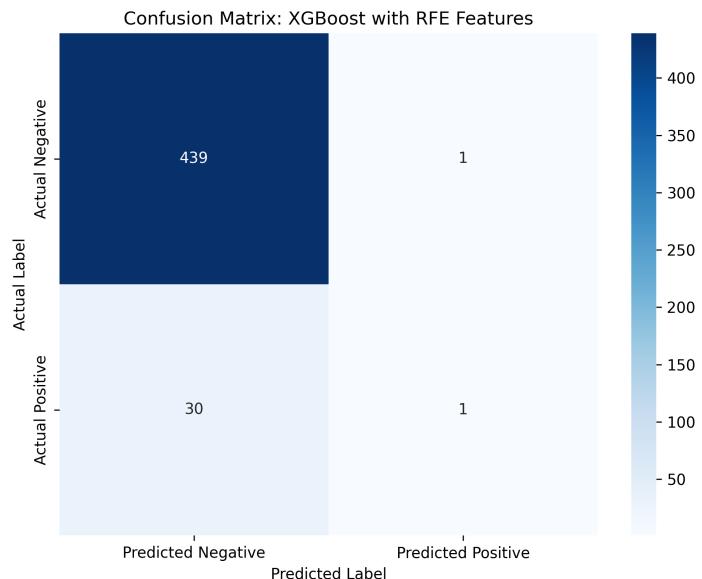
	<b>Predicted non-failure</b>	<b>Predicted failure</b>
<b>Actual non-failure</b>	TN = 439	FP = 1
<b>Actual failure</b>	FN = 30	TP = 1

Figure 4.3 presents the Linear Regression confusion matrix. Similar to SVM, Linear Regression achieves high accuracy by correctly classifying nearly all non-failure samples (high TN with very low FP). Its main limitation is again the failure class, where many positives are misclassified as negatives (high FN), leading to a low Macro F1-score. Nevertheless, compared with SVM, the non-zero Macro F1-score indicates slightly better recovery of minority-class signal under the same feature representation.



**Figure 4.3. Confusion matrix for Linear Regression on the locked SECOM test set using RFE-selected features (50 variables).**

To contrast the linear decision surfaces with a non-linear learner, Figure 4.4 shows the confusion matrix for XGBoost under the same RFE 50-feature representation. Although XGBoost matches the linear models in overall accuracy, the confusion-matrix structure highlights whether the additional model capacity translates into improved minority-class identification or simply reproduces the majority-class-dominant behavior observed for linear classifiers.



**Figure 4.4. Confusion matrix for XGBoost on the locked SECOM test set using RFE-selected features (50 variables).**

This pattern is consistent with the SECOM class-imbalance setting, where a classifier can attain high accuracy by prioritizing the majority (non-failure) class. Consequently, although the linear models appear competitive when ranked by accuracy, their limited Macro F1 performance suggests that a purely linear boundary in the selected feature space is insufficient to recover rare failure patterns without sacrificing majority-class correctness (Jiang et al., 2021; Park et al., 2024).

### 4.3.3 Generalization behavior of non-linear models

In contrast to the low-capacity linear decision surfaces, non-linear learners such as Random Forest, Decision Tree, and XGBoost possess substantially higher representational flexibility. In principle, this added capacity can be beneficial in semiconductor yield analytics, where interactions among process variables may be non-additive and threshold-driven. However, the present results indicate that increased flexibility does not automatically translate into improved minority-class detection on the locked SECOM test set.

A key observation is the presence of a measurable train–test discrepancy for the most expressive models. For example, both XGBoost and tree-based baselines achieved perfect training accuracy (1.00) while exhibiting lower test accuracy, yielding an accuracy-based Overfit Gap of 0.066 for XGBoost and 0.113 for the Decision Tree (Table 4.4). The gap is even more pronounced in Macro F1 terms: XGBoost achieved a training F1-score of 1.00 but only 0.0606 on the test set. This pattern is consistent with high-variance behavior, where the model fits idiosyncratic structure in the training distribution that does not persist under distributional noise and process variability in unseen manufacturing samples.

Importantly, the weaker test-set minority-class performance of high-capacity models in this experiment does not imply that non-linear ensembles are inherently unsuitable for SECOM yield screening. Rather, it highlights their sensitivity to noisy, high-dimensional sensor measurements when model capacity is not sufficiently constrained. In such settings, robust generalization may require tighter regularization and complexity control (e.g., limiting tree depth, increasing minimum leaf sizes, tuning learning-rate/regularization terms, or using cost-sensitive objectives that penalize failure-class miss rates more directly) (Jiang et al., 2021; Park et al., 2024).

#### **4.4 Model Generalizability (Objective 3)**

Having identified an effective feature representation in Section 4.2 (Objective 1) and benchmarked algorithmic performance under a controlled experimental setting in Section 4.3 (Objective 2), the final objective of this study focuses on evaluating model generalizability. Specifically, Objective 3 assesses whether the observed yield-screening performance can be sustained when models are exposed to previously unseen SECOM test samples—a necessary condition for practical deployment in semiconductor manufacturing environments.

While Section 4.3 showed that several models achieve high test accuracy, predictive performance alone is insufficient for industrial adoption. A deployed screening model must also demonstrate stability under distributional noise and process variability, and must avoid performance collapse when encountering new production conditions. This concern is particularly relevant in the present study because Synthetic Minority Over-sampling Technique (SMOTE) was applied during training to mitigate severe class imbalance.

Although SMOTE can improve minority-class learning, it introduces a known risk: models may learn synthetic artifacts rather than physically meaningful patterns, particularly when model capacity is high. Therefore, generalizability is evaluated by comparing training performance (on the SMOTE-augmented training data) against performance on the locked, independent test set comprising only real observations. The divergence between these phases is summarized using the Overfit Gap, where smaller gaps indicate stronger generalization capability and lower operational risk, and larger gaps indicate overfitting and reduced deployment readiness (Jiang et al., 2021; Park et al., 2024). The results of this analysis are summarized in Table 4.6, which reports the training performance obtained under the SMOTE-augmented configuration alongside the corresponding test-set performance on real, unseen SECOM samples.

**Table 4.6. Generalizability analysis quantified using the Overfit Gap under the RFE+SMOTE training configuration. A lower gap indicates a more robust and deployment-ready model.**

Model	Train Macro F1 (SMOTE)	Test Macro F1 (Real)	F1 Overfit Gap
Linear Regression	0.792	0.156	0.636 (Best)
SVM	0.798	0.160	0.639
XGBoost	1.000	0.083	0.917
Random Forest	1.000	0.049	0.951
Decision Tree	1.000	0.092	0.908

Among the evaluated models, Linear Regression exhibited the smallest F1 Overfit Gap (0.636), narrowly outperforming SVM (0.639). Although both models still display substantial gap values, their relative stability compared with the non-linear learners suggests that constrained-capacity decision functions are less prone to memorizing the SMOTE-augmented training distribution. In practical terms, the linear models retain a more consistent relationship between training and test behavior, even if their absolute failure-class detection remains limited.

In contrast, the ensemble-based methods (Random Forest and XGBoost) and the unpruned Decision Tree exhibited very large gaps (0.908–0.951). These models achieved perfect training Macro F1 (1.00) but degraded sharply on the locked test set, indicating that the learned decision rules did not transfer to real unseen samples. This pattern is consistent with high-variance behavior in high-capacity learners, where the model can form overly complex partitions that fit the augmented training distribution but fail under the natural noise and variability present in production data (Jiang et al., 2021; Park et al., 2024).

From a deployment perspective, such instability represents a critical operational risk: a model that performs well only under augmented training conditions may fail unpredictably when exposed to process drift, sensor noise, or evolving failure modes. In direct fulfillment of Objective 3, these results emphasize that generalization stability—not peak training performance—is the defining criterion for model selection in imbal-

anced yield screening. Within the tested configurations, the linear models provided the most stable (though still imperfect) generalization behavior, highlighting the importance of disciplined feature selection and controlled model complexity when building deployment-oriented predictors for the SECOM dataset.

#### 4.5 Comparison with Previous Studies

To validate the effectiveness of the proposed yield-screening pipeline, it is necessary to contextualize the obtained findings against prior research on SECOM and closely related semiconductor manufacturing datasets. Because studies differ in their prediction targets (e.g., yield screening versus virtual metrology), preprocessing choices, imbalance handling, and evaluation protocols, a strict head-to-head numerical comparison is often not possible. Therefore, the comparison below emphasizes methodological alignment (feature representation, selection strategy, and evaluation rigor) in addition to the headline performance indicators reported in the respective works.

Table 4.7 summarizes representative studies from the literature and contrasts them with the approach adopted in this project. In particular, this study contributes (i) a leak-proof evaluation design with strict train-only fitting of preprocessing and selection, (ii) an explicit comparison of wrapper (RFE) and filter (mRMR) selection under identical conditions, and (iii) a generalizability assessment using train–test performance divergence after applying SMOTE for imbalance mitigation.

**Table 4.7. Benchmarking this study against selected prior works that report classification accuracy on the SECOM dataset. Metrics are copied as stated in each reference; differences in task definition, preprocessing, imbalance handling, and evaluation protocol may limit direct numerical comparability.**

Study	Method	Feature approach	Accuracy (reported)
(Park et al., 2024)	Traditional ML + imbalance methods (SECOM)	Preprocessing sensitivity (scaling, missingness)	85.14% (best configuration reported).
(Zhao & Pang, 2024)	High-dimensional ensemble learning (SECOM)	Dimensionality reduction + ensemble comparison	90.13% (best accuracy reported).
(Zhou et al., 2023)	Quantile online learning (SECOM)	Online/streaming failure analysis	86.66% (overall accuracy reported).
(Ali et al., 2025)	Generative-model-aided fault management (SECOM)	Generative augmentation + downstream classifier benchmarking	99.78% (best test accuracy reported).
<b>This study</b>	Traditional ML benchmarking (SVM, Linear Reg., RF, DT, XGBoost)	RFE-selected subset (50 features) with leak-proof evaluation	93.42% (best test accuracy).

Overall, the literature emphasizes that semiconductor manufacturing datasets are sensitive to preprocessing and that compact, carefully selected representations can improve stability and interpretability (Kim, Eunji, et al., 2023; Park et al., 2024; Yeh et al., 2024). Consistent with these findings, the results in Sections 4.2–4.4 show that while multiple models can achieve high test accuracy on SECOM, balanced failure detection and deployment readiness are better assessed through class-sensitive metrics and generalization diagnostics. In particular, the large train–test divergences observed for high-capacity tree ensembles under imbalance mitigation highlight the importance of aligning model complexity with data characteristics and validating performance using a strict, leakage-resistant protocol.

## 4.6 Limitations

This study establishes a leak-proof benchmarking baseline for SECOM yield screening; nevertheless, several factors limit the strength and generality of the conclusions.

**Single-dataset evaluation.** All experiments were conducted using the SECOM dataset only. Without replication on additional semiconductor datasets (or on a more recent SECOM-like production dataset), the external validity of the selected preprocessing and feature-selection choices remains uncertain.

**Static, retrospective setting.** SECOM is analyzed as a fixed historical dataset. In operational environments, non-stationarity caused by tool aging, recipe changes, maintenance actions, and sensor recalibration can induce concept drift; therefore, performance measured on a locked test split may not reflect long-term deployment behavior.

**Imbalance mitigation effects.** SMOTE increases minority-class exposure during training, but the generated samples may not correspond to physically plausible process states. As a result, SMOTE can inflate apparent training performance and may exacerbate train–test divergence for high-capacity models.

**Constrained hyperparameter exploration.** Models were compared under a limited set of configurations. More extensive tuning—ideally within a nested cross-validation framework—could alter the observed performance ranking, particularly for SVM and ensemble learners.

**Cost-sensitive decision-making not optimized.** Although accuracy, Macro F1, and generalization diagnostics were reported, the evaluation did not explicitly optimize for asymmetric costs between false negatives and false positives (e.g., via threshold calibration, cost-sensitive loss functions, or expected-cost analysis).

**Limited process interpretability.** Feature selection improves tractability, but the analysis does not establish causal links between selected sensors and underlying yield-loss mechanisms. Consequently, the results are more informative for predictive screening than for root-cause diagnosis and process improvement.

## **4.7 Chapter Summary**

Chapter 4 evaluated the proposed leak-proof yield-screening pipeline on the SECOM dataset and interpreted the results in relation to the three study objectives. For Objective 1, a controlled comparison of feature-selection strategies showed that a compact 50-variable representation is feasible, and that wrapper-based RFE provided more informative subsets than filter-based mRMR when judged using class-sensitive metrics.

For Objective 2, traditional machine learning models trained on the RFE-selected feature set achieved similar high test accuracy, but Macro F1-scores remained low across most configurations, indicating that overall correctness was dominated by the majority (non-failure) class. The confusion-matrix analysis reinforced that minority (failure) detection was the primary bottleneck, and that accuracy alone is not a sufficient indicator of screening effectiveness under severe imbalance.

For Objective 3, generalizability was assessed by comparing SMOTE-augmented training performance against locked test-set performance on real observations. High-capacity tree-based learners exhibited large train–test divergences, whereas linear models showed relatively smaller overfit gaps, supporting the conclusion that stability under distributional shift is a critical selection criterion for deployment.

Finally, the chapter contextualized these findings against prior SECOM-related studies, highlighting that reported accuracy values are sensitive to experimental design choices and that rigorous, leakage-resistant evaluation is essential for credible performance claims. The combined evidence suggests that future improvements should prioritize robust minority-class detection and deployment-oriented validation, rather than maximizing training performance or headline accuracy.

## CHAPTER 5

# CONCLUSION AND FUTURE WORK

### 5.1 Overview

This chapter concludes the thesis by summarizing the principal findings from the leak-proof machine learning pipeline developed for semiconductor yield screening using the SECOM dataset. The discussion highlights the practical implications of the results for deployment in manufacturing analytics settings where data are high-dimensional, noisy, and strongly class-imbalanced. The chapter then consolidates the main contributions of the study and proposes directions for future research aimed at improving minority-class detection and long-term robustness under realistic production drift.

### 5.2 Conclusion of the Study

The primary objective of this research was to design and evaluate a reproducible, leakage-resistant workflow for predicting pass/fail outcomes from high-dimensional semiconductor sensor and test measurements. To achieve this, an end-to-end pipeline was implemented that enforces strict train-only fitting of preprocessing, class balancing, and feature selection, followed by evaluation on a locked independent test set.

The results in Chapter 4 demonstrate that rigorous data partitioning is essential for credible performance claims in SECOM-style yield screening. Under a controlled comparison of feature selection strategies, wrapper-based Recursive Feature Elimination (RFE) produced more informative 50-feature subsets than filter-based mRMR when judged using class-sensitive metrics. Although several models achieved similar headline test accuracy (up to 93.42%), Macro F1-scores remained low, indicating that overall correctness was dominated by the majority (non-failure) class. Confusion-matrix analysis confirmed that minority (failure) detection is the key bottleneck for practical screening effectiveness.

Generalizability analysis further showed that high-capacity tree-based learners can exhibit strong overfitting under SMOTE-based imbalance mitigation, achieving near-perfect training scores while degrading sharply on the real, unseen test set. In contrast, linear decision functions exhibited relatively smaller train–test divergence, suggesting that disciplined feature selection and constrained model complexity provide a more stable baseline for deployment-oriented yield screening on SECOM.

### **5.3 Contributions of the Study**

This thesis contributes a leak-proof benchmarking protocol for SECOM yield screening by enforcing an evaluation design in which the independent test set is locked prior to any scaling, imbalance handling, or feature selection, thereby ensuring that reported metrics reflect out-of-sample behavior. It also provides a systematic comparison of feature selection methods under identical preprocessing and split conditions, showing that the selection mechanism, not only the retained feature count, meaningfully affects minority-class separability in a high-dimensional and class-imbalanced setting. In addition, the work frames model comparison using deployment-relevant diagnostics beyond accuracy, emphasizing Macro F1-score, confusion matrices, and train–test divergence to quantify failure-detection quality and generalization risk when imbalance mitigation is applied. Finally, the study delivers a reproducible and modular pipeline structure that separates preprocessing, selection, training, and evaluation stages, supporting straightforward replication and extension to alternative balancing approaches, nested validation, or cost-sensitive objectives.

### **5.4 Future Work**

Although this study establishes a rigorous baseline for SECOM yield screening, several directions remain for improving minority-class detection and deployment readiness. Future research should explicitly incorporate cost-sensitive learning and threshold cali-

bration so that model optimization reflects the asymmetric consequences of false negatives and false positives in manufacturing screening. It is also important to evaluate imbalance-handling alternatives to standard SMOTE, such as borderline variants, combined over/under-sampling schemes, and ensemble-based resampling, with the goal of reducing synthetic-sample artifacts and improving transfer to real, unseen data. To reduce selection bias and stabilize reported performance, subsequent work should adopt more robust model selection strategies, including nested cross-validation and broader hyperparameter exploration, particularly for kernel-based SVMs, regularized linear models, and constrained tree ensembles. Given that fab data are commonly non-stationary, drift-aware evaluation protocols and adaptation mechanisms, including time-aware splits where applicable, drift monitoring, and periodic model updating, are also necessary for sustained performance. Beyond handcrafted feature subsets, representation learning methods for tabular sensor data, including embedding-based and attention-based models as well as self-supervised pretraining, may provide richer signal extraction if assessed under the same leakage-resistant constraints. Finally, a hybrid screening architecture that augments supervised classification with an unsupervised anomaly detection layer could improve robustness to previously unseen failure modes by flagging novel patterns that fall outside the labeled training distribution.

## 5.5 Chapter Summary

Chapter 5 summarized the thesis outcomes and emphasized that, for high-dimensional and severely imbalanced semiconductor yield screening, rigorous leakage prevention and deployment-oriented evaluation are as important as model choice. The experimental evidence indicates that minority-class detection and generalization stability remain the central challenges on SECOM, motivating future work on cost-sensitive learning, improved imbalance strategies, and drift-aware validation for real manufacturing deployment.

## **APPENDIX A**

## **APPENDIX**

### **A.1 RFE-selected feature list**

This appendix lists the 50 SECOM sensor/test variables retained after applying Recursive Feature Elimination (RFE) as the feature selection method in the proposed pipeline.

**Table A.1. List of the 50 features selected by RFE.**

<b>Feature</b>	<b>Feature</b>	<b>Feature</b>	<b>Feature</b>	<b>Feature</b>
F34	F36	F74	F138	F140
F147	F148	F152	F164	F172
F174	F176	F177	F202	F203
F204	F205	F206	F209	F221
F249	F252	F275	F282	F283
F287	F298	F307	F309	F337
F338	F340	F342	F347	F360
F387	F390	F411	F427	F434
F435	F447	F448	F469	F475
F478	F493	F494	F583	F585

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