

Review

Design of Experiments in Corrosion Research on Duplex Stainless Steels: A Systematic and Bibliometric Review

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Abstract

The corrosion behavior of duplex, superduplex, and hyperduplex stainless steels is influenced by complex interactions among compositional, microstructural, processing, and environmental variables. In this context, Design of Experiments (DOE) has been applied as a systematic approach to investigate such multivariate effects. This study presents a Systematic Literature Review (SLR) analyzing the application of DOE in corrosion studies involving duplex-family stainless steels. The review follows the PRISMA 2020 protocol and is structured using the CIMO framework. A total of 13 studies published between 2011 and 2025 were selected from the Scopus and Web of Science databases, and bibliometric analysis was conducted using the Bibliometrix package in R version 4.5.2 (2025-10-31 ucrt). The results show that DOE applications are concentrated on duplex and superduplex steels, with no studies addressing hyperduplex grades. Potentiodynamic polarization is the most frequently used technique, while Taguchi methods, Response Surface Methodology, and hybrid approaches combining DOE techniques with optimization or predictive modeling tools were among the most common methodologies identified. Most studies combine empirical modeling with qualitative interpretation, with limited integration of mechanistic and statistical approaches. Additionally, studies focus primarily on process parameters, with less emphasis on environmental variables and multi-response modeling. Taken together, this review identifies methodological research opportunities and outlines directions for strengthening the integration between statistical design and corrosion science.

Keywords: Design of Experiments; corrosion; duplex stainless steels; systematic literature review; Response Surface Methodology; Taguchi method; bibliometric analysis



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1. Introduction

Stainless steels constitute a broad class of metallic alloys whose development has been historically driven by the need to enhance corrosion resistance while maintaining adequate mechanical performance for demanding engineering applications [1]. Within this class, duplex, superduplex, and hyperduplex stainless steels have gained particular relevance due to their biphasic microstructure, composed of ferrite and austenite in balanced proportions [2]. This microstructural configuration provides a favorable combination of high mechanical strength and improved resistance to localized corrosion, especially in chloride-containing

environments, which explains their increasing adoption in industrial sectors such as oil and gas, chemical processing, and marine applications [3,4].

In engineering applications involving pipelines, pressure systems, and fluid transport infrastructure, duplex stainless steels are often considered alongside more conventional materials such as carbon steels and ductile irons [5,6]. While these materials may offer lower initial costs, duplex-family stainless steels provide a unique combination of high mechanical strength and resistance to localized corrosion [3,4].

Notwithstanding their advantageous properties, the corrosion behavior of duplex-family stainless steels remains a complex phenomenon influenced by a wide range of interacting factors [7]. Chemical composition, phase balance, alloying elements, manufacturing routes, thermal cycles, environmental conditions, and electrochemical loading parameters act simultaneously and often nonlinearly, directly affecting passivation stability and susceptibility to localized degradation mechanisms [8]. This complexity is particularly pronounced in high-strength grades, where minor variations in microstructure or processing conditions may lead to significant changes in corrosion resistance and service performance [9].

Given the multivariate and interactive nature of corrosion behavior in duplex, superduplex, and hyperduplex stainless steels, the investigation poses significant experimental challenges [10–12]. Traditional one-factor-at-a-time approaches are often insufficient to capture interaction effects and may lead to excessive experimental effort without yielding robust predictive insights [13]. In this context, formal statistical methods, particularly Design of Experiments (DOE), have emerged as essential tools for systematically exploring multiple factors, quantifying their individual and interaction effects, and developing predictive models to support process optimization and the reliable interpretation of experiments [14–16].

Several DOE techniques, including full factorial designs, Taguchi methods, and Response Surface Methodology (RSM), have been increasingly applied to studies involving welding, machining, surface modification, and heat treatment of duplex and superduplex stainless steels [17–19]. These approaches have enabled researchers to correlate process variables with corrosion-related responses, such as pitting potential, passive current density, and mass loss, thereby providing structured insights into the relationships among processing parameters, microstructure, and electrochemical performance. Representative studies have demonstrated the applicability of DOE to optimizing welding parameters and post-processing conditions in duplex stainless steels, highlighting its potential to improve corrosion resistance and experimental efficiency [20,21].

Despite increasing use of DOE in corrosion research, the literature remains fragmented and methodologically inconsistent, hindering cross-study comparisons [22]. Many studies differ substantially in their experimental design, factor definitions, response metrics, and statistical validation procedures, which hampers cross-study comparison and the consolidation of knowledge [23–26]. Furthermore, research efforts are predominantly focused on conventional duplex and, to a lesser extent, superduplex stainless steels, while hyperduplex grades, characterized by higher alloying content and increased metallurgical complexity, are rarely addressed using formal experimental design methodologies.

To contextualize the current state of knowledge, Table 1 summarizes the main review papers published in recent years on the corrosion behavior of duplex-family stainless steels.

The analysis of Table 1 shows that existing reviews predominantly focus on metallurgical and technological aspects, such as welding processes, heat treatments, additive manufacturing, microstructural evolution, phase balance, intermetallic precipitate formation, passive film stability, and electrochemical testing methodologies. Although these studies provide valuable contributions to understanding corrosion mechanisms and the

performance of duplex-family stainless steels, none systematically investigates how Design of Experiments (DOE) methodologies have been employed to study corrosion phenomena. More specifically, no previous review evaluates the application of statistical experimental design techniques, such as factorial designs, Taguchi methods, or Response Surface Methodology (RSM), for modeling, optimizing, or interpreting corrosion behavior in duplex, superduplex, or hyperduplex stainless steels.

Table 1. Main review papers about corrosion behavior of duplex-family stainless steels.

Reference	Steel Type	Main Focus	Future Directions	Journal
Gudikandula et al., 2024 [27]	Lean duplex	Effects of welding and heat treatments on microstructure and mechanical/corrosion performance	Parameter optimization and modeling approaches	<i>Sadhana Academy Proceedings in Engineering Sciences</i>
Zhou et al., 2024 [28]	Duplex	Laser powder bed fusion processing and microstructural influence on corrosion behavior	Process control and advanced corrosion studies	<i>Acta Metallurgica Sinica</i>
Liu et al., 2023 [10]	Duplex	Corrosion mechanisms (pitting, EAC)	Passive film, pitting, EAC studies	<i>Microstructures</i>
Ndukwe & Anaele, 2023 [29]	Duplex	Welding parameters and corrosion resistance of welded joints	Predictive modeling and thermal control strategies	<i>Structural Integrity and Life</i>
Mohammed et al., 2017 [30]	Austenitic & Duplex	Heat input effects on microstructure and corrosion behavior	—	<i>Metals</i>
Verma & Taiwade, 2017 [12]	Duplex	Similar and dissimilar welding processes	Thermal optimization and service life prediction	<i>Journal of Manufacturing Processes</i>
Peguet & Gaugain, 2011 [31]	Duplex & Lean	Localized corrosion and electrochemical testing criteria	—	<i>Revue de Métallurgie</i>

Prepared by the authors.

This result reveals a clear methodological gap in the literature. While corrosion mechanisms have been extensively reviewed and DOE has been increasingly applied in isolated experimental studies, there is still no structured synthesis that consolidates how experimental design techniques have been employed in corrosion research on duplex-family stainless steels. Consequently, the lack of integrative reviews at the interface between corrosion science and statistical experimental design limits the consolidation of knowledge, the identification of best experimental practices, and the development of transferable predictive models.

In this context, a Systematic Literature Review (SLR) is relevant for addressing this gap by examining how Design of Experiments (DOE) has been applied to corrosion studies of duplex, superduplex, and hyperduplex stainless steels. This approach enables the identification of experimental strategies reported in the literature, as well as methodological patterns, inconsistencies, and research areas requiring further investigation.

Accordingly, the objective of this study is to systematically analyze the scientific literature on the application of Design of Experiments (DOE) to corrosion studies involving duplex-family stainless steels. Following the PRISMA 2020 [32] protocol and structured

according to the CIMO (Context, Intervention, Mechanism, Outcome) framework [33], this review seeks to: (i) describe the experimental contexts and corrosion assessment methods adopted; (ii) identify the DOE techniques most frequently applied and the experimental factors considered; (iii) examine the relationship between experimental design and the interpretation of corrosion mechanisms; and (iv) discuss methodological patterns, limitations, and research gaps reported in the literature.

2. Materials and Methods

2.1. Search Strategy

To define the research objectives and questions, an initial exploratory search was conducted on the topic of Design of Experiments (DOE) applied to the corrosion behavior of duplex, superduplex, and hyperduplex stainless steels. The Scopus and Web of Science databases were selected due to their broad coverage of peer-reviewed scientific journals and conference proceedings [34,35].

The search strategy included combinations of terms related to experimental design and corrosion in duplex stainless steels, as follows: (“design of experiments” OR DOE OR “experimental design”) AND (“hyperduplex stainless steel” OR “hyper duplex stainless steel” OR “hyper-duplex stainless steel” OR “super duplex stainless steel” OR “superduplex stainless steel” OR “duplex stainless steel”) AND (corrosion OR “corrosion resistance” OR “corrosion behavior” OR “pitting corrosion” OR “localized corrosion” OR “electrochemical corrosion”), considering the fields title, abstract, and keywords. The search was restricted to English-language journal articles and conference papers published from 2010 onward.

2.2. Bibliometric Analysis

For the bibliographic analysis, the computational package Bibliometrix implemented in the R programming version 4.5.2 (2025-10-31 ucrt) language was employed, along with Biblioshiny version 5.2.1, the graphical interface of the Bibliometrix package version 5.2.1, which provides a comprehensive set of tools for bibliometric and scientometric research [36].

Using the R language, the thematic map shown in Figure 1 was generated.

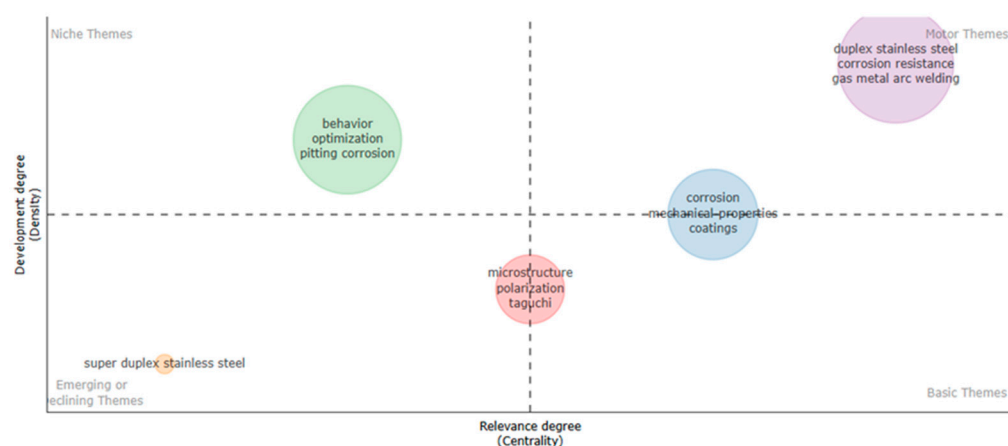


Figure 1. Thematic map. Prepared by the authors.

According to Najmaei and Sadeghinejad [37], the relevance of a theme can be assessed using a thematic map that presents a conceptual structure based on the classification of themes by their centrality and density indices. Xiao et al. [38] state that density represents the strength of internal connections among the keywords within a given theme, whereas centrality reflects the degree of interaction between that theme and other themes in the research field. As described by Guleria and Chakma (2023) [39], motor themes exhibit high centrality and high density, indicating that they are well-developed and fundamental

to the field; niche themes exhibit high density but low centrality; emerging or declining themes show low density and low centrality; and basic themes display high centrality but lower density.

As observed in Figure 1, the cluster composed of the terms “duplex stainless steel,” “corrosion resistance,” and “gas metal arc welding” is located in the motor themes quadrant, indicating that research related to corrosion resistance in duplex stainless steels, particularly under welding conditions, represents a consolidated and central research line in the literature. Terms such as “behavior,” “optimization,” and “pitting corrosion” appear in the niche themes quadrant, highlighting specialized subareas with a considerable degree of internal development. Meanwhile, terms such as “corrosion,” “mechanical properties,” and “coatings” are positioned as basic themes, demonstrating strong structural relevance within the field. In contrast, terms such as “microstructure,” “polarization,” and “Taguchi” are situated in the emerging or developing themes region, suggesting potential for the expansion of structured statistical methods in corrosion studies.

Figure 2 presents the keyword frequency analysis of the selected publications, illustrating the most frequent terms in the field of research.

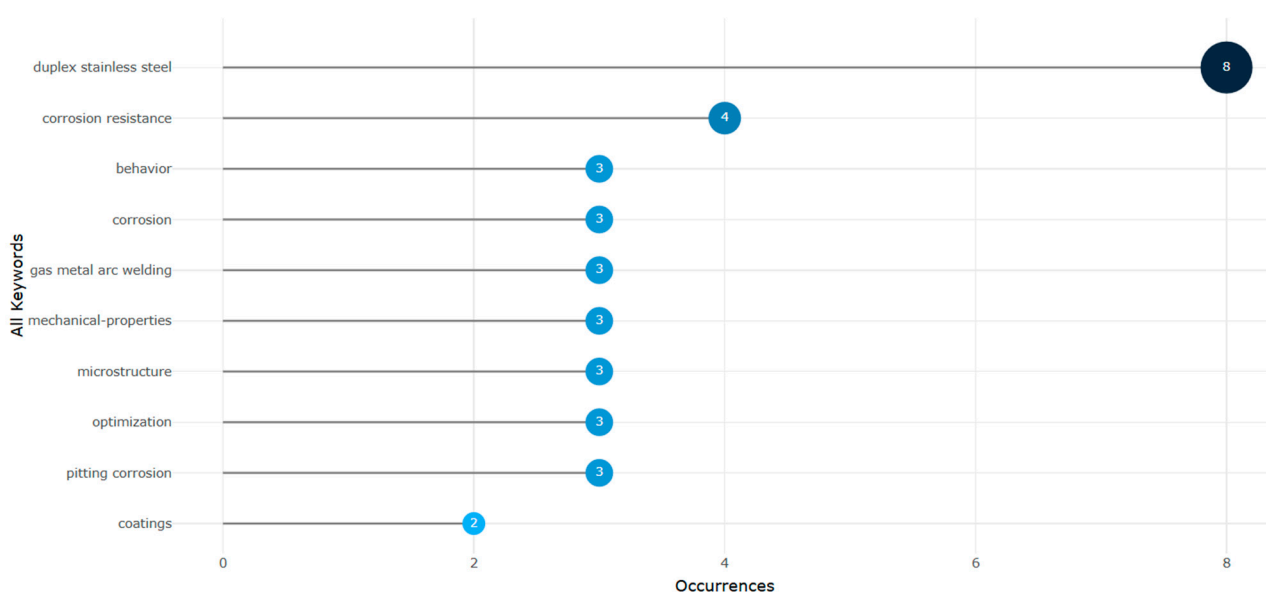


Figure 2. Keyword frequency analysis. Prepared by the authors.

As shown in Figure 2, “duplex stainless steel” is the most frequent keyword, followed by “corrosion resistance.” It should be noted that the prominence of terms such as “duplex stainless steel” and “corrosion resistance” is partially influenced by their inclusion in the search strategy used to retrieve the literature. Therefore, their high occurrence should be interpreted primarily as a characteristic of the retrieved corpus rather than as an independent indicator of emerging research themes. Nevertheless, the co-occurrence analysis remains useful for identifying secondary associations and thematic relationships among the topics investigated in the selected studies.

A considerable occurrence is also observed for terms such as “behavior,” “corrosion,” “mechanical properties,” “gas metal arc welding,” “microstructure,” “optimization,” and “pitting corrosion.” This distribution confirms the predominance of studies that associate corrosion resistance with processing conditions and microstructural characteristics. Although less frequent, the term “coatings” refers to research on surface modification strategies to improve corrosion performance.

In addition, a conceptual structure map was generated using Multiple Correspondence Analysis (MCA), a widely used technique in bibliometric studies for dimensionality

reduction and identifying relationships among terms (Dabić et al., 2023) [40]. The result is presented in Figure 3.

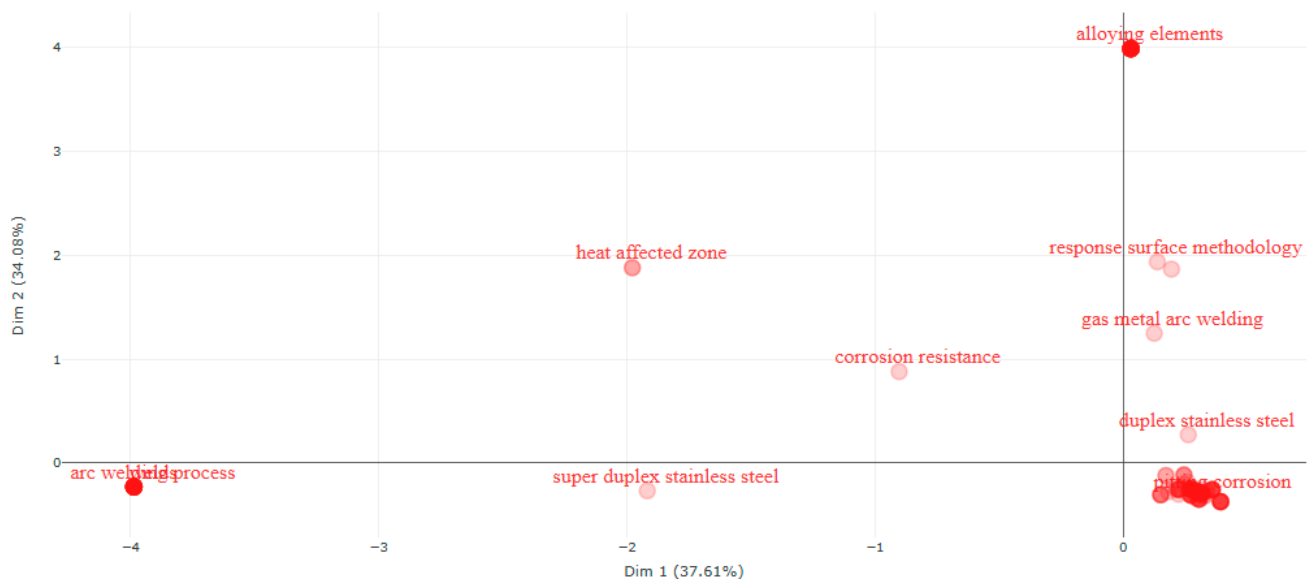


Figure 3. Multiple correspondence analysis. Prepared by the authors.

As indicated in the graphical output (Figure 3), Dim 1 accounts for 37.61% of the data variance, while Dim 2 explains 34.08%, totaling more than 71% of the variability in the two-dimensional plane. According to Majeed and Ainin (2021) [41], the proximity between points reflects greater thematic similarity, and clusters indicate correlated lines of investigation.

In Figure 3, a cluster on the right side concentrates terms such as “duplex stainless steel,” “corrosion,” “gas metal arc welding,” “Response Surface Methodology,” and “alloying elements,” highlighting an applied research stream focused on corrosion resistance associated with welding parameters, chemical composition, and statistical modeling through Response Surface Methodology. On the left side of the map, terms such as “heat-affected zone,” “super duplex stainless steel,” “welding process,” and “arc welding” stand out, representing a line of research more closely associated with microstructural alterations and thermal processing effects in the heat-affected zone.

This arrangement confirms the coexistence of two main research fronts within the field: (i) an approach centered on statistical modeling and experimental optimization aimed at improving corrosion resistance, and (ii) an approach focused on the influence of welding processes and microstructural variations on material properties.

2.3. Research Questions and CIMO Framework

Considering the structural relevance of the topic, its consolidation as a motor theme, and the increasing integration between statistical techniques and corrosion studies, the main objective of this work was to systematically investigate the application of Design of Experiments to the analysis of corrosion behavior in duplex, superduplex, and hyperduplex stainless steels, identifying trends, research gaps, and future research opportunities.

To support data extraction and result organization, the research questions were formulated based on the CIMO structure (Context, Intervention, Mechanism, Outcome), proposed by Denyer et al. [33] and widely applied in management and engineering research. In the present study, the Context refers to corrosion studies involving duplex-family stainless steels; the Intervention refers to the application of Design of Experiments methods; the

Mechanism refers to statistical modeling and the analysis of main effects and interactions; and the Outcomes refer to corrosion performance metrics and indicators.

Thus, the research questions of this Systematic Literature Review are:

(RQ1) What experimental contexts and study conditions have been considered in the analysis of corrosion behavior in duplex, superduplex, and hyperduplex stainless steels?

(RQ2) What types of experimental design approaches have been applied, and which factors are most frequently investigated?

(RQ3) How do experimental design methods contribute to identifying and modeling the mechanisms influencing corrosion resistance?

(RQ4) Which metrics and experimental responses are used to evaluate the effects of the investigated factors?

(RQ5) What research gaps and future opportunities can be identified in the application of DOE to corrosion studies in duplex stainless steels?

2.4. Search and Screening Process

Following validation of the search strings, a systematic search was conducted in the Scopus and Web of Science databases. The identification, selection, and filtering of studies were carried out in accordance with the PRISMA 2020 guidelines [42], ensuring transparency and methodological rigor throughout the review process.

Figure 4 presents the PRISMA 2020 flow diagram, which visually summarizes the stages of the study selection process and the number of records identified, screened, and included at each phase. The completed PRISMA 2020 checklist is provided as Supplementary Material.

At the identification stage, 122 studies were retrieved from the Scopus database and 95 from Web of Science, resulting in a total of 217 records prior to data cleaning. The search was restricted to English-language publications, limited to journal articles and conference papers, and covering the period from 2010 to 2025. The validated search strings were applied to the selected databases, and the resulting records were exported in CSV and TXT formats for further processing. Although the search strategy covered the period from 2010 to 2025, the earliest study satisfying all eligibility criteria was published in 2011. Consequently, the final sample comprised studies published between 2011 and 2025.

All retrieved records were consolidated into a single database. A duplicate-removal process was then conducted in R using the title, DOI, and journal name. In this step, 67 duplicate records were excluded due to overlap across the databases, and an additional 27 records were removed for failing to meet the predefined filters. As a result, 123 unique studies proceeded to the screening stage, as illustrated in the PRISMA flow diagram.

The screening process was conducted in multiple stages. The first screening stage consisted of a review of titles and abstracts to assess alignment with the scope, objectives, and inclusion criteria of this review. At this stage, 64 articles were excluded. The primary reason for exclusion was the absence of a formal statistical experimental design. Although several studies reported basic experimental planning—commonly found in empirical investigations—they did not apply structured DOE approaches such as factorial designs, Taguchi methods, or Response Surface Methodology, which are fundamental inclusion requirements for this review.

Additionally, some studies addressed corrosion behavior or microstructural aspects of duplex, lean duplex, or superduplex stainless steels but were limited to descriptive analyses and did not clearly specify the experimental design methodology in the abstract. Other excluded studies focused solely on mechanical properties, phase transformations, welding processes, machining, or microstructural characterization and did not include corrosion-related experiments. Studies based on numerical modeling, simulations, comparisons with literature data, or materials outside the scope of this review were also excluded. Review

articles discussing DOE concepts without experimental application were likewise removed. Therefore, the excluded studies at this stage did not simultaneously satisfy the criteria of employing a formal DOE methodology, conducting an experimental investigation, and focusing on the corrosion behavior of the stainless steels of interest.

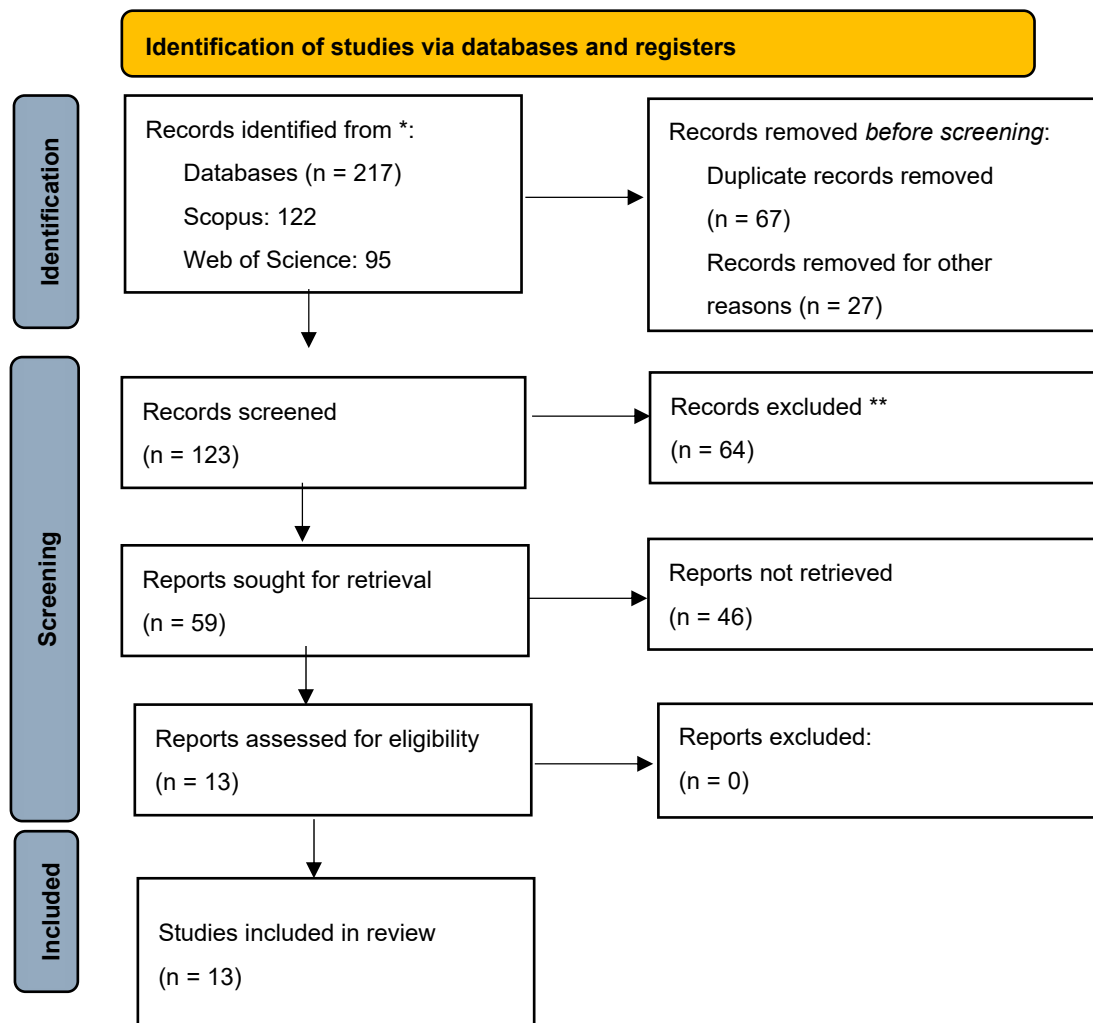


Figure 4. PRISMA 2020 flow diagram. * reported the number of records identified from each database or register searched (rather than the total number across all databases/register). ** indicated that all of them were excluded by automation tools. Prepared by the authors.

The second screening stage aimed to verify full-text accessibility. At this stage, five studies were excluded due to the unavailability of complete full-text access through the consulted databases, institutional subscriptions, or other accessible sources. The titles, abstracts, and available metadata of these studies were examined prior to exclusion. However, the absence of full-text access prevented verification of the methodological details required for inclusion in the review, particularly regarding the explicit application of DOE methodologies, corrosion-related experimental responses, and compliance with the predefined eligibility criteria. Consequently, thirteen articles remained eligible for full-text assessment and advanced to the eligibility phase.

The third screening stage involved full-text reading of the remaining studies to confirm compliance with all predefined inclusion and exclusion criteria. To ensure methodological consistency and relevance to the objectives of this systematic review, explicit a priori criteria were defined and rigorously applied at this stage.

The inclusion criteria comprised:

- Studies addressing the corrosion behavior of duplex, superduplex, or hyperduplex stainless steels;
- Explicit application of Design of Experiments (DOE) or related statistical experimental design techniques;
- Experimental studies reporting corrosion-related responses;
- Peer-reviewed publications written in English.

The exclusion criteria involved:

- Studies not involving duplex-family stainless steels;
- Papers addressing corrosion without the use of DOE or statistical experimental design methods;
- Purely numerical or simulation-based studies without experimental validation;
- Review articles, editorials, and book chapters;
- Studies lacking sufficient methodological description.

At the full-text eligibility stage, 13 reports were assessed for compliance with the predefined inclusion and exclusion criteria. No additional studies were excluded at this phase. Consequently, all 13 studies were retained for qualitative and bibliometric analysis. The exclusions at the eligibility stage were mainly due to the absence of corrosion testing despite experimental planning or to the lack of a formal statistical experimental design despite experimental execution. Additionally, upon full-text evaluation, some studies were found not to involve duplex, superduplex, or hyperduplex stainless steels, as defined within the scope of this review.

2.5. Evaluation and Synthesis

The evaluation and synthesis phase integrates evidence from the final set of selected studies using a combined quantitative and qualitative approach. This phase directly addresses the research questions (RQ1–RQ5) defined during the planning stage by systematically examining how Design of Experiments (DOE) has been applied in corrosion studies involving duplex stainless steels.

For this purpose, the selected studies were categorized according to three primary analytical dimensions:

- i Type of stainless steel investigated;
- ii Corrosion evaluation methods employed;
- iii Experimental design techniques applied.

In addition, a fourth analytical dimension was incorporated to capture the scientific maturity of the identified DOE applications: the level of statistical–mechanistic integration. While the first three dimensions enable the mapping of methodological and technological trends, this complementary dimension allows assessment of the interpretative depth of the studies and their contribution to advancing fundamental understanding of corrosion mechanisms.

The extracted information was organized in descriptive tables to examine the distribution of experimental strategies, steel grades, and characterization techniques. This organization supported the analysis of recurring approaches and the characteristics of the application of statistical tools in corrosion studies involving duplex stainless steels.

Beyond quantitative categorization, a qualitative assessment was conducted based on the clarity of the experimental design definition, the adequacy of statistical modeling, the treatment of factor interactions, and the transparency in reporting corrosion testing procedures. This assessment was not exclusionary but rather critical and interpretative, allowing evaluation of methodological rigor and robustness of the reported conclusions.

Regarding statistical–mechanistic integration, the studies were classified into three levels of scientific contribution:

- Level 1—Statistical Screening: includes studies that primarily applied statistical tools to identify significant factors and perform empirical optimization, without establishing explicit connections to microstructural evolution, phase transformations, or underlying electrochemical mechanisms.
- Level 2—Empirical Modeling with Partial Interpretation: comprises studies that fitted predictive models (e.g., RSM, regression models, or multifactor ANOVA), analyzed interaction effects, and presented discussions grounded in metallurgical or electrochemical principles. However, the mechanistic interpretation remains predominantly qualitative, lacking systematic cross-validation of statistical coefficients against microstructural or electrochemical evidence.
- Level 3—Statistical–Mechanistic Integration: encompasses studies in which statistical model parameters are explicitly linked to physical or metallurgical mechanisms, such as phase transformations, intermetallic precipitation, ferrite–austenite balance variations, or passive film stability. At this level, coherence exists between statistical modeling and complementary characterization techniques, granting the model not only predictive but also explanatory capability.

This classification should be interpreted as an analytical framework rather than a value judgment. The different levels reflect variations in scope, objectives, and methodological emphasis across studies. All levels provide valuable contributions, whether through factor screening, empirical modeling, or more in-depth mechanistic interpretations.

The inclusion of this analytical criterion allowed differentiation between studies primarily focused on statistical modeling and identification of significant factors and those that examine corrosion mechanisms in duplex stainless steels under different processing and environmental conditions.

2.6. Reporting of Results

The reporting of results was structured into two complementary and methodologically interconnected parts. This organization was adopted to ensure coherence between the quantitative mapping of the research field and the structured synthesis aimed at answering the research questions.

The first part consists of a bibliometric analysis, conducted using the Bibliometrix package in the R software environment. This stage provides a macro-level characterization of the scientific landscape concerning the application of Design of Experiments (DOE) to corrosion studies involving duplex-family stainless steels. Bibliometric indicators were used to examine annual scientific production, keyword frequency, thematic evolution, conceptual clustering, and network structures. Graphical outputs—including thematic maps, keyword co-occurrence networks, temporal evolution plots, and multiple correspondence analysis (MCA)—enabled the identification of research trends and structural patterns within the literature. This analytical layer describes how the field has evolved and how DOE methodologies are positioned within corrosion research.

The second part of the results is structured according to the CIMO framework (Context, Intervention, Mechanism, Outcome) and directly addresses Research Questions RQ1–RQ5. While the bibliometric analysis provides a structural overview, the CIMO-based synthesis presents a systematic examination of the selected studies in relation to the defined analytical dimensions.

Within this framework:

- The Context dimension examines the experimental conditions, material grades (duplex, superduplex, hyperduplex), and corrosion assessment methods adopted in the literature (RQ1);

- The Intervention dimension identifies the types of Design of Experiments approaches employed and the most frequently investigated experimental factors (RQ2);
- The Mechanism dimension evaluates how statistical modeling contributes to the interpretation of corrosion behavior, including interaction modeling, validation procedures, and levels of statistical–mechanistic integration (RQ3);
- The Outcome dimension analyzes the corrosion performance metrics and response variables used to evaluate the effects of the investigated factors (RQ4);
- Finally, the integrative interpretation across these dimensions supports the identification of research gaps and future opportunities (RQ5).

This two-part organization establishes a clear distinction between the structural characterization of the field and the interpretative analysis of the selected studies. The bibliometric analysis describes the configuration and thematic evolution of the literature, whereas the CIMO-based synthesis systematizes the evidence in direct relation to the research questions. The combination of these approaches enables a general overview of the field and a detailed examination of methodological practices reported in studies applying DOE to corrosion research involving duplex stainless steels.

3. Results

3.1. Bibliometric Overview

The bibliometric analysis conducted in this review aimed to characterize the scientific landscape concerning the application of Design of Experiments (DOE) to corrosion studies involving duplex-family stainless steels. The final dataset comprises investigations focused on duplex and superduplex stainless steels published between 2011 and 2025. Beyond quantifying publication output, the analysis seeks to identify thematic evolution, methodological consolidation, and structural patterns within the research field.

Figure 5 presents the annual scientific production of the selected studies.

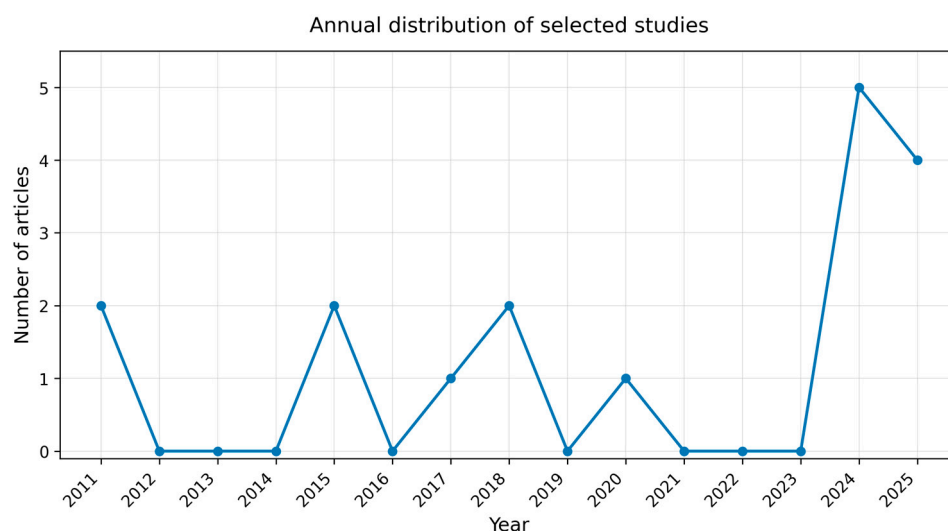


Figure 5. Annual scientific production. Prepared by the authors.

Between 2011 and 2023, publication output remained irregular and relatively sparse, with isolated years yielding one or two contributions interspersed with periods when no studies meeting the established criteria were identified. This discontinuous pattern suggests that, for more than a decade, the application of structured experimental design methodologies to corrosion studies in duplex-family stainless steels did not constitute a consolidated research trajectory. Instead, DOE-based approaches appear to have been employed sporadically, likely as complementary tools rather than as central methodological frameworks.

From 2024 onward, publication frequency increases markedly, followed by sustained output in 2025. This recent intensification reflects growing recognition of the need for statistically structured, improvement-oriented experimental strategies in corrosion research. The shift may reflect broader trends in materials engineering, where multifactorial phenomena and performance optimization increasingly demand systematic experimental planning rather than conventional one-variable-at-a-time approaches.

Overall, the temporal distribution reveals two distinguishable phases: an initial stage characterized by low methodological consolidation and limited recurrence of DOE-based studies, and a more recent phase marked by accelerated publication growth and stronger methodological engagement.

Figure 6 illustrates the temporal evolution of the most recurrent terms identified in the selected studies. Each horizontal line represents the time span during which a given keyword appeared in the analyzed literature. In contrast, the size of the circles represents the relative frequency of that keyword in the dataset, as calculated by Bibliometrix software. Therefore, the figure illustrates thematic evolution and the relative prominence of research topics over time rather than the exact annual number of publications containing each keyword.

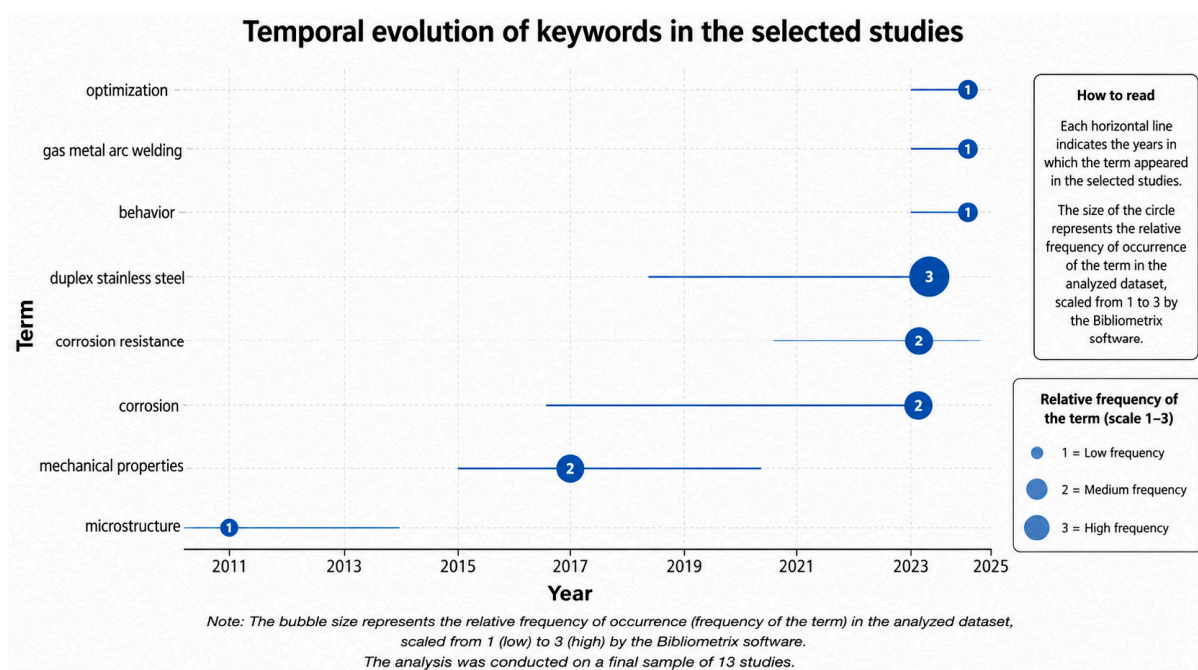


Figure 6. Temporal evolution of the most recurrent keywords identified in the selected studies. Horizontal lines indicate the period during which each keyword appeared in the analyzed literature. Circle size represents the relative frequency of occurrence of the keyword in the dataset, as computed by the Bibliometrix software. Prepared by the authors.

In the earlier years of the analyzed period, terms such as microstructure were more prominent, indicating an initial focus on metallurgical characterization and phase-related investigations. This emphasis suggests that early studies predominantly explored corrosion behavior through descriptive and structural analyses of phase balance and microstructural features.

As the field progressed, terms associated with broader performance evaluation, such as mechanical properties and corrosion, became more frequent. This transition signals a shift from purely microstructural characterization to integrated performance assessment that incorporates both mechanical and electrochemical responses.

In the most recent years, a higher concentration of terms such as corrosion resistance, duplex stainless steel, and optimization has become evident. The growing prominence of optimization is particularly significant, as it reflects the increasing incorporation of statistically structured approaches for parameter adjustment and response modeling. This evolution indicates not merely thematic diversification but also methodological maturation, marked by a transition from descriptive experimentation to quantitatively driven, model-based research strategies.

Additionally, the appearance of application-oriented terms such as gas metal arc welding demonstrates the expansion of DOE methodologies into specific industrial contexts, particularly those involving thermally induced microstructural transformations and their impact on corrosion performance.

Figure 7 presents the keyword co-occurrence network derived from the selected studies, revealing the field's conceptual organization. The network exhibits well-defined thematic clusters structured around the central node, duplex stainless steel, which shows the highest degree of connectivity. This centrality confirms that the material itself functions as the integrative axis linking diverse investigative approaches.

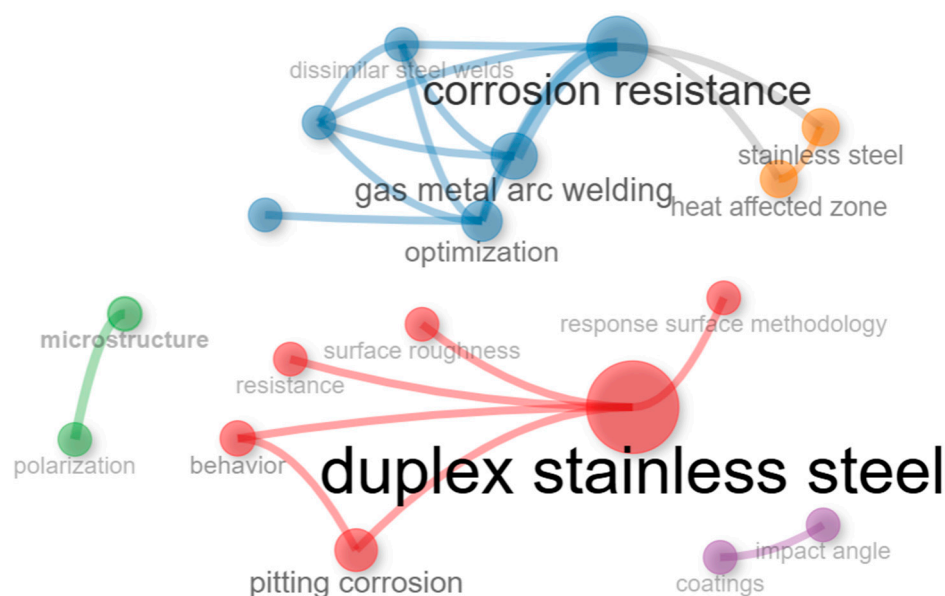


Figure 7. Keyword co-occurrence network. Prepared by the authors.

In Figure 7, a prominent cluster can be observed, strongly associated with corrosion resistance and welding-related terms, such as gas metal arc welding (GMAW), dissimilar steel welds, and the heat-affected zone. The proximity of these terms indicates that a significant portion of the literature focuses on corrosion behavior in welded joints, where microstructural heterogeneity and thermal cycles introduce complex interactions between phase distribution, residual stresses, and electrochemical response. In this context, DOE-based approaches are frequently employed to systematically evaluate the influence of welding parameters on corrosion performance.

Another relevant cluster, shown in Figure 7, is organized around Response Surface Methodology (RSM) and is closely connected to terms such as pitting corrosion, surface roughness, and behavior. This configuration suggests that RSM is the predominant operational framework for implementing DOE in this domain. Rather than being broadly conceptualized as a unified methodological field, DOE applications appear to be concentrated around specific statistical techniques, particularly those oriented toward response modeling and optimization of localized corrosion phenomena.

The cluster linking microstructure and polarization, shown in Figure 7, highlights investigations centered on electrochemical testing and metallurgical characterization, emphasizing the interplay between phase constitution and corrosion mechanisms. In contrast, peripheral groupings involving coatings and impact angle suggest more specialized application scenarios, potentially related to erosion–corrosion environments and surface engineering strategies.

Importantly, the network shown in Figure 7 does not reveal a highly centralized methodological cluster explicitly structured around the broader concept of Design of Experiments. Instead, structured experimental approaches are embedded within application-specific clusters, particularly welding optimization and pitting corrosion modeling. This configuration indicates that, although DOE techniques are increasingly applied, the field has not yet consolidated around a strongly unified methodological identity.

Taken together, the bibliometric evidence indicates that research on DOE applied to corrosion in duplex-family stainless steels is organized across distinct yet interconnected thematic domains. These domains encompass welding parameter optimization, localized corrosion modeling, electrochemical characterization, and surface engineering applications. The observed evolution reflects a gradual transition from microstructural description to performance-oriented, statistically structured, and optimization-driven investigations, highlighting the expanding yet still consolidating role of DOE methodologies in corrosion research on duplex stainless steels.

3.2. Analysis According to the CIMO Framework

To address the research questions posed in this review, the selected studies were examined against the CIMO dimensions: Context (RQ1), Intervention (RQ2), Mechanism (RQ3), and Outcome (RQ4). In addition, the integrative interpretation across these dimensions supports the identification of research gaps and future opportunities (RQ5). The following subsections present the main results.

3.2.1. Context—Experimental Conditions and Materials (RQ1)

The analysis of the experimental context focused on the types of duplex-family stainless steels investigated and the general conditions under which corrosion behavior was examined.

The contextual dimension of this review examined the types of duplex-family stainless steels investigated in studies that applied Design of Experiments (DOE) to corrosion assessment. Table 2 presents the distribution of material categories identified in the analyzed studies.

Table 2. Distribution of duplex-family stainless steel grades in the analyzed studies.

Steel Type	Percentage
Duplex	73%
Superduplex	27%
Hyperduplex	0%

Prepared by the authors.

As shown in Table 2, conventional duplex stainless steels account for 73% of the analyzed studies, followed by superduplex grades (27%). No study explicitly addressed hyperduplex stainless steels. This finding is noteworthy because hyperduplex stainless steels were explicitly included in the search strategy and eligibility criteria. Therefore, their absence from the final sample should be interpreted as a feature of the current literature rather than a limitation of the review scope.

The predominance of conventional duplex grades indicates that DOE-based corrosion investigations are primarily concentrated on materials with established industrial relevance and widespread research presence. This distribution suggests that structured experimental planning has been more frequently incorporated into studies of alloys that are already well-established in the literature.

Superduplex steels are also represented, demonstrating that statistically designed experimental approaches have been applied to higher-alloyed duplex systems. However, their proportion remains lower than that of conventional duplex grades. Based solely on the extracted data, this distribution cannot be attributed to specific technological or economic factors, but it reflects a concentration of DOE applications within the most frequently investigated duplex categories.

The absence of hyperduplex steels in the analyzed sample indicates that higher-performance duplex alloys appear less frequently in statistically designed corrosion investigations. Considering the potential of these materials in aggressive environments, this scenario may suggest opportunities for expanding DOE applications to more complex duplex systems.

Based on the analyzed sample, the contextual distribution indicates that DOE applications in corrosion research involving duplex-family stainless steels have predominantly focused on conventional, well-established alloy grades.

In addition to material categorization, the experimental context was further characterized by the corrosion assessment methods employed in the selected studies. Table 3 presents the distribution of corrosion analysis techniques identified in the analyzed sample.

Table 3. Distribution of corrosion analysis type.

Category	Techniques Included	Percentage (Estimated)
Electrochemical	Potentiodynamic, Anodic, EIS, OCP	~55%
Mass Loss	FeCl ₃ immersion (ASTM G48), Gravimetry	~15%
Surface/Mechanical	Slurry Erosion, Roughness (Ra/Rz), Pitting Density	~20%
Structural/Others	Micro-hardness, Ferrite Content (como resposta)	~10%

Prepared by the authors.

As shown in Table 3, electrochemical techniques are the most frequently employed approach, accounting for approximately 55% of the studies analyzed. This category includes potentiodynamic and anodic polarization methods, as well as electrochemical impedance spectroscopy (EIS) and open circuit potential (OCP) measurements. These techniques enable determination of key corrosion parameters, including corrosion potential (E_{corr}), corrosion current density (i_{corr}), pitting potential (E_{pit}), and polarization resistance. Their predominance indicates that quantitative electrochemical analysis remains central to statistically structured corrosion investigations involving duplex-family stainless steels.

Mass loss-based approaches account for approximately 15% of the studies and include standardized corrosion tests, such as FeCl₃ immersion (ASTM G48), as well as gravimetric measurements. These methods emphasize material degradation by directly quantifying mass loss under controlled, aggressive environments, providing performance indicators compatible with statistical modeling frameworks, even though they are not based on electrochemical measurements.

Surface and mechanical characterization techniques represent around 20% of the analyzed studies. This category includes evaluations of slurry erosion, surface roughness

(Ra/Rz), and pitting density. These approaches focus on surface integrity and degradation mechanisms associated with combined or localized corrosion, extending the analysis beyond purely electrochemical metrics while still providing quantifiable responses suitable for DOE-based modeling.

Finally, structural and other characterization methods account for approximately 10% of the studies. These include microhardness measurements and ferrite content evaluation, which serve as response variables. Although not direct measures of corrosion, these parameters are often related to material performance and degradation behavior, contributing to a broader understanding of the factors influencing corrosion resistance.

The distribution presented in Table 3 indicates that, while electrochemical techniques remain the principal methodological approach, DOE-based corrosion studies are not restricted to conventional electrochemical responses. The inclusion of mass-loss measurements, surface-integrity assessments, erosion-related parameters, and microstructural indicators demonstrates that researchers have increasingly employed DOE to investigate corrosion as a multidimensional phenomenon. This broader experimental perspective enables the simultaneous evaluation of degradation mechanisms, material performance, and process-related variables, highlighting DOE's versatility as a tool for corrosion research involving duplex-family stainless steels.

The predominance of electrochemical techniques reflects their ability to provide rapid, quantitative, and statistically robust response variables, making them particularly suitable for DOE-based optimization studies.

3.2.2. Intervention—Experimental Design Approaches Applied (RQ2)

The Intervention dimension of this review focused on the types of Design of Experiments (DOE) techniques employed to investigate corrosion performance in duplex-family stainless steels. Table 4 summarizes the distribution of experimental design methodologies identified in the selected studies.

Table 4. Distribution of DOE type.

DOE Type	Percentage (Estimated)
Full factorial design	8%
Response Surface Methodology (RSM)	25%
Taguchi method	33%
Hybrid (Taguchi + RSM/optimization approaches)	33%

Prepared by the authors.

In the present review, the term “hybrid design” refers to approaches that combine a structured DOE methodology, such as Taguchi designs, with complementary optimization, modeling, or prediction techniques, including Response Surface Methodology (RSM), regression-based models, artificial neural networks (ANNs), and multi-response optimization procedures. These approaches seek to combine the experimental efficiency of DOE with enhanced predictive and optimization capabilities.

The results indicate that both the Taguchi method and hybrid experimental approaches account for the largest proportions of the sample, each at 33% of the selected studies. The presence of hybrid structures reflects the combination of orthogonal arrays with response surface modeling, regression adjustment, or multi-response optimization techniques. In these cases, Taguchi designs are frequently used to structure factor arrangements, while complementary modeling procedures are employed to refine the prediction and optimization stages.

The application of the Taguchi method (33%) indicates the continued use of orthogonal arrays for structured parameter screening and evaluation of factor influence, with fewer experimental runs. This approach is associated with efficient experimental planning, systematic comparison of factor levels, and the pursuit of more robust operating conditions amid experimental variability, particularly through signal-to-noise ratios and variability-control strategies.

Response Surface Methodology (25%) appears as an independent methodological strategy in three studies. In these cases, the objective is generally to develop second-order polynomial models to describe the combined influence of multiple variables on corrosion-related responses. The use of regression modeling within RSM reflects an interest in representing continuous response behavior across defined experimental domains.

The full factorial design accounts for 8% of the sample and appears in a single study. This approach enables explicit evaluation of interaction effects and complete mapping of factor combinations within predefined levels. Its lower frequency suggests that fully crossed designs are less commonly adopted compared to more economical or sequential modeling strategies.

The predominance of Taguchi and hybrid methodologies suggests that corrosion researchers favor experimental strategies that reduce the number of experimental runs while still capturing the effects of multiple interacting variables. This preference is particularly relevant in corrosion studies, where electrochemical testing, long-term exposure experiments, and microstructural characterization can be time-consuming and resource-intensive. The adoption of hybrid approaches further indicates a growing interest in combining efficient experimental planning with predictive modeling and process optimization.

Taken together, the distribution indicates that DOE applications in corrosion research involving duplex stainless steels are characterized by a balance between screening-oriented designs and model-based optimization approaches. The significant proportion of hybrid methodologies suggests that several studies integrate structured experimental matrices with regression-based modeling to support prediction and parameter adjustment.

Within the scope of the Intervention dimension, in addition to the type of experimental design, the experimental factors considered as input variables in the DOE models were also analyzed. Based on the coding performed during the CIMO analysis, a consistent thematic pattern emerges across the reviewed studies.

Most DOE applications are centered on process-related parameters, particularly those associated with welding operations, heat input control, and electrical discharge machining conditions. Variables such as welding current, pulse current, travel speed, shielding gas flow rate, heating time, and discharge parameters appear recurrently in the literature. This indicates a research orientation focused on evaluating how manufacturing and processing conditions influence subsequent corrosion behavior.

A second group of studies investigates mechanical and erosion-related variables, including impact velocity, impingement angle, flow velocity, and erodent characteristics. These parameters are typically examined in erosion-corrosion contexts, where both mechanical degradation and electrochemical processes are considered.

Environmental variables, such as temperature, salinity, chloride concentration, pH, and CO₂ presence, also appear in the sample, although with comparatively lower recurrence than process parameters. These factors are directly associated with corrosion kinetics and electrochemical stability but are less frequently positioned as primary DOE input variables.

This distribution indicates that DOE-based investigations in duplex stainless steel corrosion research are predominantly focused on process parameter analysis and optimization, while environmental chemistry variables receive comparatively less emphasis in structured experimental designs. This imbalance suggests that future DOE applications

should increasingly incorporate environmental variables together with processing parameters to better reproduce the complex service conditions experienced by duplex-family stainless steels.

3.2.3. RQ3—Mechanism

Research Question 3 aimed to determine the extent to which Design of Experiments (DOE) methodologies contribute not only to the statistical identification of significant factors but also to the mechanistic understanding of corrosion behavior in duplex, superduplex, and hyperduplex stainless steels. In this context, the analysis considered the structural characteristics of the statistical models—particularly the inclusion of interaction terms and higher-order effects, the presence of validation procedures, and the level of statistical–mechanistic integration, classified into three levels.

The inclusion of interaction effects and quadratic terms was observed in a substantial proportion of studies, particularly those employing factorial designs and Response Surface Methodology. From a statistical perspective, these terms increase model flexibility and enable the representation of nonlinear behavior and interdependent process variables. In corrosion systems, where parameters such as temperature, current density, impact velocity, shielding gas flow, and heat input may act synergistically, the ability to model interactions is particularly relevant. However, the results indicate that the presence of statistically significant interaction coefficients does not necessarily correspond to mechanistic integration. In several cases, interaction terms remained confined to the regression structure, without an explicit physical interpretation linking the coefficients to phase transformations, variations in ferrite–austenite balance, intermetallic precipitation, or passive film stability.

Experimental validation was conducted in the majority of the analyzed studies, typically through confirmation runs or comparison between predicted and experimental responses. Although validation enhances predictive robustness and supports the reliability of optimization, it does not inherently confer explanatory power. A statistically accurate model may still lack physical interpretability if its coefficients are not connected to metallurgical or electrochemical mechanisms. Therefore, validation was interpreted as an indicator of methodological rigor rather than mechanistic depth.

Based on these criteria, the reviewed studies were classified into three levels of statistical–mechanistic integration. Level 1 (Statistical Screening) comprises studies in which DOE was applied primarily for empirical optimization and identification of significant factors, without explicit linkage to microstructural evolution or electrochemical mechanisms. At this level, corrosion responses are treated as black-box outputs. Level 2 (Empirical Modeling with Partial Interpretation) represents the predominant category. These studies employed regression models, Response Surface Methodology, Taguchi methods, or multifactor ANOVA, frequently including interaction terms, and complemented the statistical analysis with microstructural characterization or electrochemical measurements. Nevertheless, the mechanistic interpretation remained predominantly qualitative, lacking systematic cross-validation of regression coefficients against independently measured microstructural or electrochemical parameters. Level 3 (Statistical–Mechanistic Integration) was identified in a limited subset of studies in which statistical model parameters were explicitly linked to physical or metallurgical mechanisms. At this level, coherence exists between statistical modeling, microstructural evidence, and electrochemical indicators, granting the model both predictive and explanatory capability.

A synthesis of the interaction structure, validation procedures, and integration levels is presented in Table 5.

Table 5. Interaction Structure, Validation Procedures, and Levels of Statistical–Mechanistic Integration in the Analyzed Studies.

Author (Year)	Level	Integration Summary
Yousefieh et al. (2011) [43]	2	Microstructural analysis and metallurgical discussion, without formal integration into the statistical model.
Mesquita et al. (2011) [44]	2	Microstructure used as an experimental factor with mechanistic discussion, but the model remains empirical.
Mohammed et al. (2015) [45]	2	DOE combined with auxiliary physical model (heat input) and microstructural analysis, without integration into the statistical model.
Varatharajulu et al. (2015) [46]	1	Purely empirical modeling (RSM), without microstructural or physical analysis.
Ratnayake & Dyakov (2016) [47]	2	Statistical model with qualitative microstructural interpretation, not incorporated into DOE.
Abdollahi et al. (2018) [48]	2	Correlation between heat input and corrosion supported by microstructural analysis, without formal integration.
Kesavalu & Subramanian (2024) [49]	1–2	Empirical modeling with qualitative physical interpretation, not incorporated into the model.
Annamalai et al. (2024) [50]	2	Microstructural characterization and physical discussion, not included in the statistical/ ANN model.
Kuruvila et al. (2024) [51]	2–3	Microstructural analysis and erosion mechanisms, with a purely empirical final model.
Melad et al. (2024) [52]	2	RSM with physical interpretation, without microstructural variables in the model.
Kuruvila et al. (2025) [53]	3	Integration of statistical model with electrochemical and microstructural evidence (cross-validation).
Policena et al. (2025) [54]	3	Statistical identification of effects with explicit mechanistic integration.
Dhairiyasamy & Gabriel (2025) [55]	2	DOE + RSM with physical interpretation, without integrated mechanistic modeling.

Prepared by the authors.

The distribution of integration levels indicates a predominance of Level 2 studies, suggesting that the combination of empirical modeling and qualitative mechanistic interpretation represents the most common approach in the literature. In these studies, microstructural characterization and electrochemical analysis are frequently used to support a posteriori explanations of statistically significant effects. However, this information is rarely incorporated as explicit variables or parameters in the models' mathematical structure.

Although interaction effects, regression models, and validation procedures are commonly reported, explicit statistical–mechanistic integration, in which statistical coefficients are associated with physically relevant phenomena such as phase transformations, intermetallic precipitation, ferrite–austenite balance, or passive film stability, appears in a more specific subset of studies. This aspect indicates that increasing statistical complexity through higher-order terms or interaction effects may occur independently of the level of mechanistic interpretation adopted.

In general, the findings suggest that DOE has been predominantly used as a predictive, optimization-oriented tool rather than as a framework for developing structurally inte-

grated statistical–mechanistic models. The main limitation identified is not the absence of statistical rigor but the lack of systematic strategies for incorporating physically meaningful variables, such as phase fractions, transformation kinetics, or electrochemical parameters, into regression models.

Consequently, while DOE remains highly effective for factor screening and process optimization, its potential to support deeper mechanistic understanding in corrosion studies of duplex stainless steels is still only partially explored, representing a relevant opportunity for future research.

This finding suggests that the future development of corrosion research in duplex-family stainless steels may benefit from integrating DOE methodologies with physically informed variables and mechanistic descriptors, enabling the transition from purely predictive models toward more explanatory and scientifically interpretable frameworks.

3.2.4. RQ4—Outcomes: Corrosion Metrics and Performance Indicators

The analysis of the response variables adopted in the selected studies reveals a clear predominance of electrochemical metrics as primary indicators of corrosion performance in duplex and superduplex stainless steels. Most investigations structured within Design of Experiments (DOE) frameworks employed parameters derived from potentiodynamic or cyclic polarization tests, with pitting potential (E_{pit}), corrosion potential (E_{corr}), corrosion current density (i_{corr}), and polarization resistance (R_p) as the most frequent responses.

This focus on discrete electrochemical variables suggests that statistical models developed in DOE applications tend to evaluate specific indicators of passivity and susceptibility to localized corrosion. In particular, pitting potential frequently appears as the target variable for maximization, reflecting its practical relevance in chloride-containing industrial environments. Similarly, corrosion current density is widely used as a quantitative indicator of the electrochemical degradation rate and is commonly modeled with linear or quadratic regression, with ANOVA support.

Despite the predominance of these metrics, most studies rely on univariate optimization strategies, modeling a single primary response at a time. Only a limited number of investigations adopt multi-response optimization techniques, such as desirability functions, integrating variables such as pitting potential, corrosion current density, and mechanical properties simultaneously. This limitation suggests that although DOE is consolidated as a tool for parameter adjustment and process optimization, its application for integrated performance modeling remains relatively restricted.

Beyond strictly electrochemical parameters, part of the analyzed literature incorporates physicomachanical responses associated with degradation under aggressive conditions. These include mass loss according to standardized procedures (e.g., ASTM G48), pitting density, surface roughness parameters (R_a , R_z), and three-dimensional topographical descriptors. Such indicators broaden the conventional polarization-based approach by incorporating morphological and surface integrity aspects into statistical optimization processes.

Additionally, a subset of studies investigates erosion or erosion–corrosion phenomena, employing responses such as erosion rate, post-processing roughness, or material removal rate. Although these investigations do not directly use electrochemical metrics, their response variables are treated as proxies for performance under severe service conditions, indicating a methodological expansion of DOE applications beyond strictly electrochemical corrosion assessment.

An important finding emerging from the synthesis is that, although microstructural indicators, such as ferrite–austenite phase balance, intermetallic precipitation (σ , χ , Cr_2N), pit morphology, and local chemical composition, are frequently characterized through optical microscopy, SEM/EDS, and X-ray diffraction, these parameters are rarely quan-

titatively incorporated as independent variables within the statistical models. In most cases, microstructural evidence serves as qualitative interpretative support for explaining trends observed in electrochemical responses rather than as an integrated component of the regression structure.

Overall, the results indicate that response variables in DOE-based corrosion studies of duplex stainless steels remain largely centered on classical electrochemical indicators, with limited integration of multiple outcomes and restricted quantitative incorporation of microstructural parameters. This finding highlights the need for future experimental strategies that combine multi-response modeling, quantitative microstructural variables, and deeper statistical–mechanistic integration, thereby enhancing the explanatory and predictive capabilities of corrosion performance models.

The predominance of electrochemical response variables reflects the central role of passivity and localized corrosion resistance in the evaluation of duplex stainless steels. However, the limited incorporation of quantitative microstructural descriptors into statistical models suggests that many DOE applications remain focused on performance prediction rather than on establishing direct relationships between microstructural evolution and corrosion mechanisms. Expanding the use of integrated response variables may therefore represent an important step toward more physically informed corrosion models.

3.3. Synthesis of Experimental Findings from DOE-Based Corrosion Studies

Beyond identifying the experimental design strategies employed in corrosion research, the selected studies provide important insights into the variables governing the corrosion performance of duplex-family stainless steels.

Welding-related parameters were the most frequently investigated variables among the selected studies. Using the Taguchi method, Yousefieh et al. [43] demonstrated that pulse current was the dominant factor affecting the pitting corrosion resistance of UNS S32760 super duplex stainless steel welds, accounting for more than 66% of the variation in pitting potential. Similarly, Abdollahi et al. [48] optimized pulsed-current gas arc welding parameters for dissimilar joints between UNS S32750 and AISI 321, demonstrating that appropriate combinations of pulse current, background current, and pulse frequency significantly improved corrosion resistance. More recently, Melad et al. [52] employed Response Surface Methodology (RSM) to investigate TIG welding of 2205 DSS and reported that optimized welding current, welding speed, and nitrogen-containing shielding gas increased the critical pitting potential while maintaining hardness levels close to those of the base metal.

The importance of heat input has been consistently reported in welding studies. Mohammed et al. [45] found that corrosion resistance improved with increasing heat input during friction welding of UNS S31803 duplex stainless steel, attributing this behavior to favorable microstructural evolution and the preservation of the ferrite–austenite phase balance. Consistently, review studies have highlighted that heat input plays a fundamental role in determining the microstructure, corrosion resistance, and mechanical properties of duplex stainless steels, emphasizing that excessively low heat inputs should be avoided because they may impair phase balance. Likewise, Dhairiyasamy et al. [55] showed that controlled welding energy in dissimilar DSS2205/SS316L joints resulted in refined microstructures, improved tensile strength, and reduced corrosion rates.

Environmental factors were investigated in fewer studies but were shown to significantly influence corrosion behavior. Mesquita et al. [44] applied a factorial design to evaluate the effects of heat treatment and CO₂ on the corrosion behavior of UNS S32750 super duplex stainless steel. Their results revealed that CO₂ concentration significantly affected the corrosion potential, corrosion current density, and polarization resistance,

highlighting the importance of considering environmental variables alongside metallurgical factors.

Another important research direction involved erosion and erosion–corrosion phenomena. Annamalai et al. [50] used a Taguchi design to investigate slurry erosion of 2205 DSS and found that impact velocity and slurry concentration were the most influential variables affecting mass loss. Surface analyses revealed ductile erosion mechanisms dominated by micro-cutting, ploughing, indentation, and lip formation. Similarly, Kuruvila et al. [51] optimized the solid-particle erosion resistance of thermally sprayed NiCr coatings deposited on duplex stainless steel and identified the impact angle, flow velocity, and particle feed rate as critical variables. More recently, Kuruvila et al. [53] combined Taguchi optimization with electrochemical characterization and demonstrated that optimized erosion conditions reduced the corrosion rate of eroded DSS 2205 surfaces by approximately 50%.

The reviewed literature also indicates increasing interest in manufacturing-related variables that may indirectly influence corrosion performance. Policena et al. [54] investigated the surface integrity of milled duplex stainless steels and demonstrated that surface roughness and machining-induced defects strongly influenced pitting susceptibility. Accelerated corrosion tests showed pit nucleation preferentially occurring within machining grooves and surface irregularities. These findings support the concept that surface integrity is a key factor governing the initiation of localized corrosion.

Several studies also indicate that corrosion performance cannot be considered independently of mechanical and surface-related properties. Melad et al. [52] simultaneously evaluated pitting corrosion resistance and hardness in TIG-welded DSS 2205, while Dhairiyasamy and Gabriel [55] reported that optimized welding conditions improved both corrosion resistance and tensile strength. Similarly, investigations involving erosion, surface roughness, and machining-induced defects demonstrated that variables affecting corrosion behavior often influence wear resistance, surface integrity, and overall material performance. These observations suggest that DOE methodologies can support multi-response optimization strategies that balance corrosion resistance with mechanical and structural requirements, a capability particularly relevant to engineering applications where both durability and load-bearing capacity must be considered.

Collectively, the reviewed studies demonstrate that DOE methodologies are valuable not only for process optimization but also for identifying the variables that most strongly control corrosion performance. Welding parameters, heat input, environmental conditions, erosion variables, and surface integrity factors were repeatedly identified as significant contributors to corrosion behavior. The literature further suggests that future investigations should integrate metallurgical, environmental, and operational variables within unified DOE frameworks to better represent the complex service conditions experienced by duplex-family stainless steels.

These findings demonstrate that DOE applications in corrosion research have progressed beyond simple parameter optimization and now increasingly contribute to the identification of the physical and operational factors governing corrosion performance in duplex-family stainless steels.

3.3.1. QP5—Current Issues and Future Perspectives

Current Issues

The literature analysis reveals consistent progress in the application of Design of Experiments (DOE) methodologies to corrosion studies involving duplex-family stainless steels. However, the findings from RQ1–RQ4 indicate that several methodological limitations recur across the reviewed studies, particularly regarding statistical–mechanistic integration, multi-response optimization, incorporation of environmental variables, and ex-

ploration of advanced duplex grades. These aspects may benefit from further development in future research.

A first aspect concerns the level of integration between statistical modeling and mechanistic interpretation. Although the reviewed studies frequently employ factorial designs, Taguchi methods, or Response Surface Methodology (RSM), most approaches focus primarily on predictive regression modeling, with predominantly qualitative mechanistic discussions. The quantitative incorporation of microstructural and electrochemical variables directly into regression equations remains relatively limited, indicating an opportunity for methodological advancement.

Another observation is the predominance of univariate modeling strategies, in which responses such as pitting potential or corrosion current density are analyzed individually. Considering the multifactorial nature of corrosion phenomena, multi-response approaches may provide a more integrated understanding of the interactions among electrochemical, microstructural, and environmental variables.

It was also noted that environmental variables, such as temperature, chloride concentration, and pH, although widely recognized as critical factors in corrosion kinetics, are not always incorporated as primary independent variables in experimental matrices. In many cases, the focus is placed predominantly on processing or manufacturing parameters. Expanding experimental designs to systematically include service-relevant environmental conditions may enhance the industrial applicability and robustness of future studies.

Additionally, no studies were identified that apply DOE methodologies to investigate corrosion in hyperduplex stainless steels. These alloys, typically characterized by elevated chromium, molybdenum, and nitrogen contents, are designed for operation in highly aggressive chloride-containing environments. However, their increased alloying complexity may also intensify susceptibility to secondary-phase precipitation, microsegregation, and passive-film instability under improper thermal or environmental conditions. Given this heightened multivariable sensitivity, hyperduplex stainless steels represent a material class for which statistically structured experimental designs would be particularly appropriate to capture interaction effects and nonlinear responses. The absence of studies at this interface, therefore, reflects not only a quantitative gap but also a missed opportunity for deeper methodological and mechanistic exploration.

Taken together, the still limited number of identified studies suggests that the systematic application of DOE in corrosion research involving duplex stainless steels remains in a phase of consolidation, offering substantial room for expansion and methodological refinement. Rather than representing a limitation of the review methodology, the relatively small number of eligible studies identified through the PRISMA screening process reflects the current maturity level of this highly specialized research field. This finding highlights both the emerging nature of DOE applications in duplex stainless steel corrosion studies and the opportunities for future investigations.

Future Perspectives

Based on the identified aspects, several research directions appear particularly relevant for advancing the field.

First, strengthening the integration between statistical modeling and metallurgical fundamentals may yield more explanatory models that systematically incorporate quantitative microstructural descriptors and passive film characteristics into statistical analyses.

Second, adopting multi-response optimization strategies may support more comprehensive analytical frameworks, enabling the simultaneous evaluation of corrosion resistance, mechanical performance, and surface integrity, as well as potential trade-offs among them. Such approaches may be particularly valuable for structural and industrial

applications in which both durability and load-bearing capability must be considered during material and process optimization.

Another relevant perspective is to expand experimental matrices to explicitly incorporate environmental variables that are representative of real-world service conditions, such as high chloride concentrations and thermal gradients.

Furthermore, the application of DOE methodologies to the corrosion behavior of hyperduplex stainless steels represents a promising and underexplored research avenue, with potential to broaden current understanding of these alloys under diverse experimental conditions.

Finally, future studies may benefit from integrating DOE methodologies with computational modeling, machine learning techniques, and advanced microstructural characterization tools. Such approaches could support the development of statistically robust and physically informed models that simultaneously describe processing conditions, microstructural evolution, environmental exposure, and corrosion performance. This integration may represent an important step toward more predictive and mechanistically interpretable corrosion frameworks for duplex-family stainless steels.

4. Conclusions

This Systematic Literature Review provides a systematic mapping of the application of Design of Experiments (DOE) in studies addressing the corrosion behavior of duplex-family stainless steels. Grounded in the CIMO framework and conducted in accordance with the PRISMA 2020 protocol, the review identified methodological patterns, dominant corrosion assessment approaches, and underexplored research directions in the existing literature.

The analyzed studies reveal a clear focus on duplex stainless steels, followed by superduplex grades, which are predominantly investigated under electrochemical corrosion conditions. Potentiodynamic polarization emerges as the most frequently employed technique, reflecting a strong emphasis on localized corrosion mechanisms. From a methodological perspective, the widespread adoption of Taguchi methods, Response Surface Methodology (RSM), and factorial designs highlights the growing recognition of DOE as an effective tool for structuring experiments, reducing variability, and identifying influential process parameters in corrosion-related investigations.

Despite the formal application of DOE across the reviewed studies, the results indicate that its use is often oriented toward factor screening and process optimization, with limited integration into deeper mechanistic interpretations linking statistical outcomes to electrochemical and microstructural phenomena. This suggests that future research could benefit from more advanced, integrative experimental designs that simultaneously address multiple responses and strengthen the connection between statistical modeling and corrosion mechanisms.

A critical and consistent finding of this review is the complete absence of experimental studies that apply DOE to the corrosion behavior of hyperduplex stainless steels. This gap, confirmed across both qualitative synthesis and bibliometric analyses, persists despite the increasing industrial relevance of these alloys. As such, hyperduplex stainless steels represent a promising and underexplored domain for future research, particularly when investigated through structured experimental design frameworks combined with corrosion testing and microstructural characterization.

The present review consolidates the state of the art in DOE-based corrosion studies of duplex and superduplex stainless steels and clearly delineates methodological and material-related research gaps. By mapping existing practices and highlighting unexplored intersections among DOE, corrosion mechanisms, and advanced alloy classes, the study provides a robust foundation for future investigations to advance both the scientific understanding and practical optimization of corrosion-resistant materials.

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