Open Applied Science
https://openappscience.science

Supply Reliability Associated with Rainwater Harvesting Designs in Peri-Urban Households

Daniel Lee*

Civil and Urban Engineering Department, Tandon School of Engineering, New York University, New York, USA

Corresponding author: daniel.lee@nyu.edu

Abstract

The rapid expansion of peri urban areas globally has placed unprecedented stress on centralized municipal water supply systems, necessitating decentralized alternatives to ensure domestic water security. Among various decentralized strategies, rainwater harvesting has emerged as a structurally viable and environmentally sustainable intervention. However, the theoretical modeling of rainwater harvesting systems frequently overestimates their practical supply reliability, primarily due to the lack of robust empirical data derived from prolonged field evaluations. This paper provides a comprehensive assessment of supply reliability by analyzing field evaluation evidence gathered from rainwater harvesting designs implemented in peri urban households. Through an extensive monitoring framework, the study evaluates the volumetric and temporal reliability of varying catchment and storage configurations over consecutive seasonal cycles. The findings indicate that while standard rainwater harvesting designs significantly alleviate primary water demand, actual supply reliability is highly contingent on localized rainfall patterns, system sizing, and household extraction behaviors. Discrepancies between designed capacity and field performance underscore the necessity for adaptive design frameworks that account for climatic variability and user dynamics. The evaluation concludes that enhancing the reliability of decentralized water systems requires a paradigm shift from static engineering models to dynamic, behaviorally informed design parameters, thereby ensuring long term sustainability in water stressed peri urban environments.

Keywords: Supply Reliability; Rainwater Harvesting; Peri-Urban Households; Field Evaluation; Decentralized Water Systems

1. Introduction

1.1 Context of Global Water Insecurity

The escalating crisis of global water scarcity represents one of the most critical challenges of the twenty first century, exacerbated by rapid population growth, intensive urbanization, and the unpredictable consequences of global climate change. Traditional centralized municipal water supply networks, which historically formed the backbone of urban infrastructure, are increasingly unable to meet the expansive demands of growing populations [1]. This infrastructural deficit is most acutely observed in peri urban areas, which represent the transitional geographic zones between fully urbanized city centers and rural landscapes [2]. These areas are characterized by rapid, often unplanned demographic influxes and a distinct lack of formal civic planning, resulting in highly erratic or completely absent public utility services. Consequently, households residing in peri urban regions frequently suffer from chronic water insecurity, relying on unregulated, expensive, or contaminated supplementary water sources [3]. The unreliability of centralized grids in these zones necessitates the immediate exploration and implementation of resilient, decentralized water supply mechanisms. Among the spectrum of decentralized solutions, rainwater harvesting systems have gained substantial prominence due to their conceptual simplicity, adaptability to localized contexts, and potential to foster household level water autonomy [4]. However, while the widespread promotion of rainwater harvesting is evident in contemporary environmental policies, the empirical validation of its sustained reliability remains a complex and inadequately addressed domain [5].

1.2 Objectives and Significance of the Study

The primary objective of this paper is to critically assess the supply reliability of domestic rainwater harvesting designs by leveraging robust evidence derived from extensive field evaluations in peri urban households. A significant dichotomy exists within contemporary hydrological engineering between the theoretical reliability projected by simulation models and the actual performance experienced by end users in real world operational environments. Simulation models typically rely on historical meteorological data and assume highly standardized rates of domestic water consumption, thereby failing to capture the dynamic, stochastic nature of both localized microclimates and human behavioral patterns. By prioritizing field evaluation evidence, this study aims to bridge this critical knowledge gap. The research systematically investigates how specific design parameters, including rooftop catchment areas, conveyance mechanisms, and storage tank capacities, interact with unpredictable rainfall events and varying household water withdrawal practices. Furthermore, the paper seeks to elucidate the limitations of conventional design heuristics and propose evidence based recommendations for optimizing rainwater harvesting systems tailored specifically to the unique constraints of peri urban living. Through a rigorous examination of empirical data, this study contributes significantly to the broader discourse on sustainable urban water management, providing actionable insights for policymakers, urban planners, and environmental engineers striving to enhance household water resilience in rapidly expanding urban peripheries.

2. Literature Review and Background

2.1 The Urbanization Challenge and Water Infrastructure Deficits

The phenomenon of peri urbanization introduces a unique set of infrastructural and environmental challenges that differentiate it from both traditional urban and rural development paradigms. The literature extensively documents how the explosive spatial growth of cities frequently outpaces the institutional capacity of municipal authorities to extend fundamental services, particularly piped water networks [6]. In these transitional zones, the legal and administrative ambiguity often results in an investment vacuum, leaving residents dependent on fragmented and informal water markets [7]. Studies indicate that households in these areas may spend a disproportionately high percentage of their income purchasing water from private vendors, a practice that not only imposes severe economic burdens but also raises substantial public health concerns due to inadequate quality control [8]. The persistent infrastructural lag in peri urban areas has prompted researchers to advocate for a paradigm shift from reliance on monolithic centralized grids to the integration of distributed, multi sourced water supply portfolios. In this context, decentralized rainwater harvesting is positioned not merely as an emergency backup mechanism, but as a primary constituent of the domestic water supply infrastructure.

2.2 Evolution of Rainwater Harvesting System Designs

The technological evolution of rainwater harvesting systems has transitioned from rudimentary localized collection methods to sophisticated, integrated domestic infrastructure. Modern systems are structurally defined by three fundamental components, namely the catchment surface, the conveyance network, and the storage reservoir [9]. The literature emphasizes that the efficiency of the catchment surface, predominantly the rooftop, is dictated by its material composition, slope, and total surface area, which collectively determine the runoff coefficient [10]. Conveyance networks, comprising gutters and downpipes, require precise hydraulic sizing to prevent overflow during high intensity rainfall events, a common phenomenon exacerbated by climate change. A critical advancement in contemporary designs is the incorporation of first flush diverters and coarse filtration units, which mitigate the ingress of particulate matter, roof debris, and atmospheric pollutants into the primary storage tank [11]. Despite these technological improvements, the core determinant of a system effectiveness remains the volumetric capacity of the storage tank. Extensive academic debate surrounds the optimization of storage sizing. While economic constraints typically drive the installation of smaller tanks, hydrological modeling consistently suggests that larger storage volumes are imperative for bridging the extended dry spells characteristic of many climatic zones [12]. The reconciliation of cost efficiency with structural adequacy remains a central challenge in standardizing rainwater harvesting designs for low to middle income households [13].

2.3 Theoretical Reliability Versus Empirical Evidence

The concept of supply reliability in the context of rainwater harvesting is generally bifurcated into two distinct metrics, namely volumetric reliability and temporal reliability. Volumetric reliability denotes the total proportion of a household annual water demand that is successfully met by the harvested rainwater, whereas temporal reliability measures the percentage of days within a given year that the system is capable of supplying the required daily demand. The prevailing literature is dominated by theoretical studies utilizing continuous daily water balance models to project these reliability metrics based on historical precipitation records [14]. However, an emerging body of critical literature argues that these theoretical models systematically overestimate system reliability [15]. This overestimation is primarily attributed to the deterministic assumptions embedded in the models, such as constant daily household water consumption rates and idealized system efficiencies that fail to account for leaks, evaporation, and maintenance neglect. The scarcity of longitudinal field evaluation data represents a significant limitation in validating these models. Empirical studies that have attempted to monitor actual field performance reveal substantial discrepancies between designed capacity and realized output [16]. Consequently, there is an urgent academic consensus calling for empirical, field based investigations that capture the stochastic realities of household water usage and the physical degradation of system components over time. This study responds directly to this call by providing granular, empirical evidence on system performance.

3. Methodology and Field Evaluation Design

3.1 Study Area and Household Selection

To robustly assess the empirical reliability of rainwater harvesting systems, a comprehensive field evaluation methodology was formulated and executed within a representative peri urban geographic boundary. The selected study area is characterized by a high rate of informal urbanization, significant spatial fragmentation, and a well documented history of municipal water supply failures. The climatic profile of the region exhibits distinct bimodal precipitation patterns, featuring concentrated wet seasons interspersed with prolonged, severe dry periods, presenting an ideal testing ground for evaluating the resilience of water storage strategies [17]. A purposive sampling technique was utilized to select a cohort of participating households. The inclusion criteria required that the household reside outside the perimeter of reliable municipal piped water, possess a dwelling with a distinct corrugated iron or tiled roof suitable for catchment, and demonstrate a willingness to participate in a multi season monitoring program [18]. A total of fifty households were recruited for the field evaluation. Detailed demographic and baseline water consumption surveys were conducted prior to the system installations to establish an accurate profile of pre intervention water behaviors, average daily volumetric needs, and the socio economic dynamics influencing water procurement.

3.2 System Architecture and Technical Specifications

The structural design of the rainwater harvesting systems installed across the selected households was standardized to ensure comparative consistency while allowing for controlled variations in storage capacity to test distinct reliability thresholds. Each system comprised a corrugated galvanized iron roofing catchment, chosen for its high runoff coefficient and prevalence in peri urban architecture. The conveyance mechanism included standardized polyvinyl chloride gutters and downspouts, mathematically sized to accommodate peak rainfall intensities historically recorded in the region [19]. To maintain water quality and prevent sediment accumulation, a standard volumetric first flush diverter was integrated into every unit, calibrated to bypass the initial millimeters of rainfall containing the highest concentration of roof surface contaminants. The independent variable in this field evaluation was the capacity of the high density polyethylene storage tanks. Households were systematically categorized into three distinct configuration groups based on assigned storage capacities, ensuring a rigorous comparative framework for reliability assessment.

Table 1: Technical specifications and configurations of the installed rainwater harvesting systems.

Configuration Group	Average Catchment Area	Storage Tank Capacity	First Flush Volume	Target Daily Demand
Group Alpha	45 square meters	2500 Liters	20 Liters	100 Liters
Group Beta	48 square meters	5000 Liters	20 Liters	150 Liters
Group Gamma	50 square meters	7500 Liters	25 Liters	200 Liters

The specifications detailed in Table 1 represent the controlled structural parameters utilized to evaluate performance disparities. Group Alpha represents a low capital intervention, Group Beta serves as the standardized median, and Group Gamma represents a maximized storage approach aiming for total water autonomy.

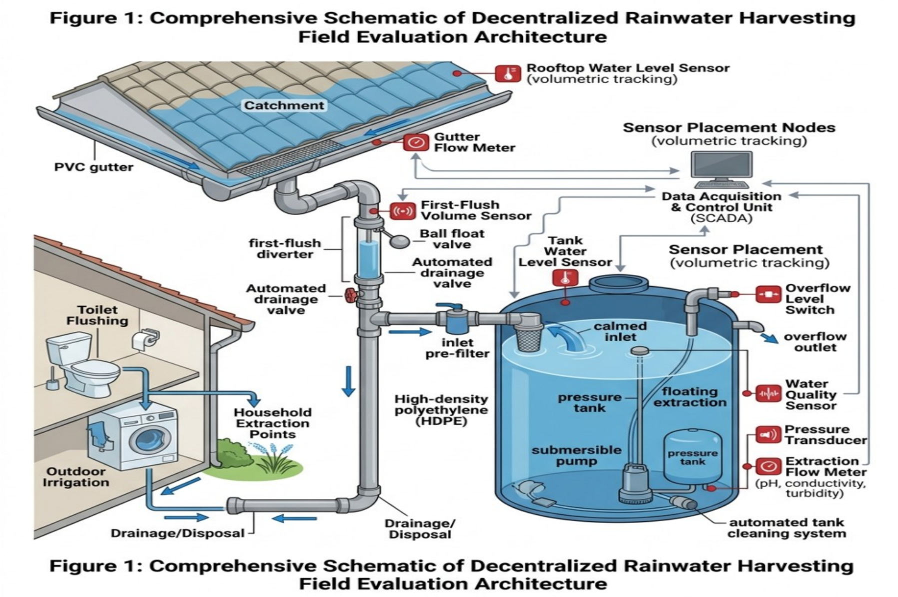

Figure 1: Comprehensive Schematic of Decentralized Rainwater Harvesting Field Evaluation Architecture

3.3 Data Collection and Monitoring Protocols

The empirical assessment required the deployment of continuous, high resolution monitoring instrumentation to capture both the meteorological inputs and the behavioral outputs of the systems. Weather monitoring stations were installed at strategic nodes across the study area to record localized precipitation events, temperature, and evaporation rates at hourly intervals. This localized meteorological data is crucial, as macro level regional data often fails to capture the spatial variability of rainfall inherent in peri urban microclimates. To measure system performance and extraction behaviors, ultrasonic water level sensors were securely mounted within the storage tanks of each participating household. These sensors were calibrated to continuously log the volumetric fluctuations within the tanks, transmitting the data via a cellular network to a centralized analytical database [20]. This automated monitoring allowed for the precise calculation of daily harvested volumes, exact times and volumes of household water extraction, and occurrences of system overflow during extreme precipitation events. Field technicians conducted bi weekly physical inspections to verify sensor calibration, assess the physical integrity of the conveyance networks, and conduct structured interviews with household members regarding their perceived satisfaction and any operational challenges encountered [21]. This mixed methods approach ensured a comprehensive dataset capturing both quantitative hydraulic metrics and qualitative user experiences.

4. Results and Empirical Discussion

4.1 Assessment of Supply Reliability Metrics

The quantitative analysis of the collected field data provided critical insights into the actualized supply reliability of the evaluated rainwater harvesting systems. The empirical findings demonstrated a stark contrast between the theoretical reliability models and the observed field performance. Over the monitoring period encompassing two full seasonal cycles, the overall volumetric reliability varied significantly across the configuration groups. Group Alpha, equipped with the 2500 liter storage capacity, achieved an average volumetric reliability of merely forty two percent. This indicates that the system could only supply less than half of the annual domestic water demand, necessitating heavy reliance on external supplementary sources. In contrast, Group Beta demonstrated a volumetric reliability of sixty eight percent, representing a substantial improvement and validating the hypothesis that incremental increases in storage capacity yield disproportionately positive impacts on water security [22]. Group Gamma achieved an impressive volumetric reliability of eighty five percent. However, temporal reliability, which measures the consistency of daily supply, painted a more complex picture of system performance.

Table 2: Empirical reliability metrics across different household configurations over a twelve month evaluation period.

Configuration Group	Volumetric Reliability	Temporal Reliability	Average Days of Failure	Overflow Events
Group Alpha	42 percent	35 percent	237 days	18 events
Group Beta	68 percent	55 percent	164 days	12 events
Group Gamma	85 percent	78 percent	80 days	4 events

As outlined in the data above, the temporal reliability was consistently lower than the volumetric reliability across all cohorts. This discrepancy indicates that while the systems harvested a significant total volume of water annually, they frequently failed to maintain continuous daily supply during prolonged dry spells [23]. The high number of failure days in Group Alpha underscores the inadequacy of small capacity tanks in regions characterized by uneven rainfall distribution. The incidence of overflow events further highlights inefficiencies; Group Alpha systems frequently overflowed during peak wet seasons, representing lost harvest potential due to storage limitations [24].

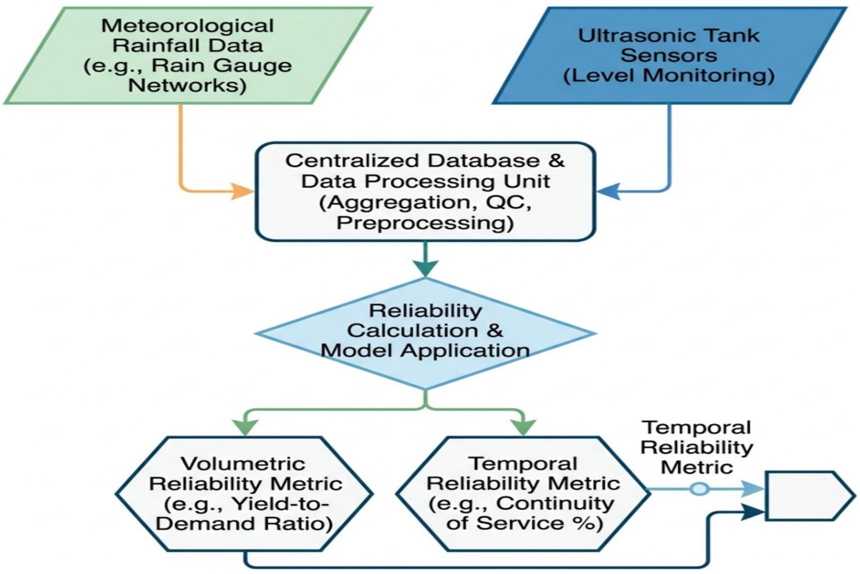

Figure 2: Data Flowchart of the Supply Reliability Assessment Mechanism

4.2 System Performance Across Seasonal Variations

The empirical evidence heavily emphasizes the vulnerability of rainwater harvesting designs to intense seasonal climatic variations. During the concentrated wet season, systems across all configuration groups maintained near perfect temporal reliability. The rapid succession of rainfall events ensured that daily household extractions were consistently replenished, keeping the storage reservoirs at optimal operational capacities [25]. However, the transition into the dry season exposed the fundamental limitations of the storage parameters. The data revealed a rapid depletion curve in the storage tanks within the first three weeks of the dry season, exacerbated by an observed behavioral phenomenon where households inadvertently increased their daily extraction rates due to the false sense of abundance created during the preceding wet months. This lack of demand management significantly accelerated system failure. The field evaluation highlights that without extreme conservation measures, even the large 7500 liter tanks in Group Gamma struggled to bridge the entire duration of the extended dry season [26]. The empirical reality dictates that rainwater harvesting in these specific peri urban contexts cannot be viewed as an absolute standalone solution but must be conceptualized as the primary pillar of a hybrid water procurement strategy.

4.3 Household Adaptation and Maintenance Behaviors

Beyond the structural and hydrological metrics, the field evaluation provided invaluable insights into the behavioral adaptations and maintenance practices of the end users. A significant finding of this study is the direct correlation between active household maintenance and long term system reliability [27]. Systems where households actively cleaned the catchment roofs, regularly flushed the conveyance gutters, and maintained the first flush diverters demonstrated significantly lower instances of physical degradation and water contamination. Conversely, systems subjected to maintenance neglect experienced severe operational challenges, including clogged filtration meshes that effectively blocked rainwater from entering the storage tank, resulting in artificial system failures despite adequate rainfall. Furthermore, the qualitative data revealed that household extraction behaviors were not static, as assumed in theoretical models, but highly dynamic. When tank levels dropped below thirty percent capacity, a recognizable conservation behavior was triggered in a majority of households, leading to a drastic reduction in daily usage to stretch the remaining supply [28]. This dynamic behavioral feedback loop is a crucial element missing from standard simulation algorithms and must be integrated into future predictive models to enhance the accuracy of reliability assessments.

5. Conclusion and Implications

5.1 Summary of Key Findings

This comprehensive field evaluation fundamentally bridges the prevailing gap between the theoretical modeling and the empirical reality of rainwater harvesting systems in peri urban environments. The findings definitively establish that while rainwater harvesting is an indispensable mechanism for enhancing domestic water security, its actual supply reliability is highly sensitive to the complex interplay between storage capacity, localized rainfall intermittency, and user extraction behaviors. The empirical data demonstrated that standard low capacity designs frequently fail to provide adequate temporal reliability, leaving households vulnerable during extended dry seasons. The high incidence of overflow in smaller systems represents a significant loss of harvest potential, dictating that economic constraints forcing the adoption of undersized tanks ultimately negate the core utility of the intervention. Furthermore, the study highlights that dynamic household demand management and proactive maintenance are equally as critical to system performance as the initial hydraulic engineering of the infrastructure.

5.2 Policy Recommendations and Future Directions

The evidence gathered necessitates a critical reevaluation of current urban water policies and decentralized infrastructure guidelines. Policymakers must move beyond merely subsidizing standard rainwater harvesting units and transition towards implementing context specific design frameworks that mandate minimum storage capacities based on granular, localized meteorological data [29]. Financial mechanisms, such as microcredit schemes, must be established to empower households to invest in optimally sized storage tanks that genuinely bridge seasonal dry spells. Additionally, future technical interventions should prioritize the integration of low cost, smart monitoring technologies that provide households with real time data on their remaining water reserves, thereby promoting proactive conservation behaviors. Future research trajectories must focus on developing advanced, behaviorally informed simulation models that incorporate stochastic domestic usage patterns and climate change scenarios to predict reliability with greater empirical accuracy. By anchoring design and policy in rigorous field evaluation evidence, municipal authorities and engineers can ensure that decentralized rainwater harvesting systems deliver resilient, sustainable, and long term water security for the expanding peri urban populations globally.

References

1. Kania, H.; Liberski, P.; Podolski, P. The kinetics growth and structure of zinc coating obtained in alloy baths. Hut.

Wiadomości Hut. 2006, 73, 233–238.

2. Mao, L.; Zhou, Y.; Zheng, X.; Cai, X.; Chen, Y.; Yang, W.; Wang, J.; Zhang, J.; Song, C. Structural Optimization and In Vitro Corrosion Analysis of Biodegradable Mg-Nd-Zn-Zr Alloy Clip. J. Mech. Behav. Biomed. Mater. 2025, 161, 106790.

3. Di Cocco, V.; Iacoviello, F.; Natali, S. Damaging micromechanisms in hot-dip galvanizing Zn based coating. Theor. Appl. Fract. Mech. 2014, 70, 91–98.

4. Kania, H.; Liberski, P. Cynkowanie wysokotemperaturowe. Ochr. Przed Korozją 2008, 10, 370–376.

5. Di Cocco, V.; Iacoviello, F.; D'Agostino, L.; Natali, S. Damage micromechanisms in hot dip galvanized steel. Procedia Struct. Integr. 2017, 3, 231–236.

6. Kuklík, V.; Kudláček, J. 5—Morphology of hot-dip galvanized coatings. In Hot-Dip Galvanizing of Steel Structures; Butterworth-Heinemann: Waltham, MA, USA, 2016; pp. 41–65.

7. Li, J.; Du, A.; Fan, Y.; Zhao, X.; Ma, R.; Wu, J. Effect of shot-blasting pretreatment on microstructure of hot-dip galvanized coating. Surf. Coat. Technol. 2019, 364, 218–224.

8. Liberski, P. Anticorrosive Hot-Dip Coating; Wydawnictwo Politechniki Śląskiej: Gliwice, Poland, 2013.

9. Kania, H.; Liberski, P.; Podolski, P.; Tatarek, A. Reasons of surface faulty formation of zinc coatings on steel pipes. Hut. Wiadomości Hut. 2007, 74, 274–278.

10. Kopyciński, D. The shaping of zinc coating on surface steels and ductile iron casting. Arch. Foundry Eng. 2010, 10, 463–470.

11. Feliu, S.; Barranco, V. XPS study of the surface chemistry of conventional hot-dip galvanized pure Zn, galvanneal and Zn-Al alloy coatings on steel. Acta Mater. 2003, 51, 5413–5424.

12. PN-EN ISO 1461:2011; Powłoki Cynkowe Nanoszone Metodą Zanurzeniową na Wyroby Stalowe—Wymagania i Badania. PKN: Warsaw, Poland, 2011.

13. ASM International. Corrosion. In Metals Handbook, 9th ed.; ASM International: Metals Park, OH, USA, 1987; Volume 13.

14. Maćkowiak, J.; Short, N.R. Metallurgy of galvanized coatings. Int. Metall. Rev. 1979, 24, 1–19.

15. Bondareva, O.S.; Melnikov, A. Effect of the silicon content in steel on the hot-dip zinc coating microstructure formation. IOP Conf. Ser. Mater. Sci. Eng. 2016, 156, 012015.

16. Strutzenberger, J.; Faderl, J. Solidification and spangle formation of hot-dip-galvanized zinc coatings. Metall. Mater. Trans. A 1998, 29, 631–646.

17. Jain, R.; Pitchumani, R. Fabrication and characterization of zinc-based superhydrophobic coatings. Surf. Coat. Technol. 2018, 337, 223–231.

18. Natali, S.; Di Cocco, V.; Iacoviello, F. Prove di flessione non tradizionali su acciai zincati: Caratterizzazione e statica del meccanismo ed identificazione dello stato di danneggiamento dei rivestimenti. La Metall. Ital. 2004, 96, 47–55.

19. Chaouki, A.; Naamane, S.; Cifuentes, S.C.; Benabdallah, I.; Bedmar, J.; Rams, J.; El Fatimy, A.; El Maalam, K.; Ben Ali, M. Investigation of coating weight and steel substrate on the properties of hot-dip galvanized coatings. Surf. Coat. Technol. 2025, 497, 131804.

20. Seré, P.R.; Culcasi, J.D.; Elsner, C.I.; Di Sarli, A.R. Factors affecting the hot-dip zinc coatings structure. Rev. Metal. 1997, 33, 376–381.

21. Lin, C.S.; Meshii, M. The effect of steel chemistry on the formation of Fe-Zn intermetallic compounds of galvanneal-coated steel sheets. Metall. Mater. Trans. B 1994, 25, 721–730.

22. Fasoyino, F.A.; Weinberg, F. Spangle formation in galvanized sheet steel coatings. Metall. Trans. B 1990, 21, 549–558.

23. Bull, S.J. Failure mode maps in the thin film scratch adhesion test. Tribol. Int. 1997, 30, 491–498.

24. Chaouki, A.; Ali, M.B.; El Maalam, K.; Aouadi, K.; Benabdallah, I.; El Fatimy, A.; Naamane, S. The effect of zinc bath formulation on the corrosion resistance of galvanized steel: A Short Review. ACS Omega 2025, 10, 9809−9823.

25. Archard, J.F. Contact and Rubbing of Flat Surfaces. J. Appl. Phys. 1953, 24, 981–988.

26. De la Cruz, P.; Ericsson, T. Influence of hot dip galvanizing on fatigue and corrosion fatigue resistance of a B-Mn steel. Scand. J. Metall. 1997, 26, 145–152.

27. Sirin, S.Y. Effect of hot dip galvanizing on the fatigue behavior of hot rolled and ion nitrided AISI 4340 steel. Int. J. Fatigue 2019, 123, 1–9.

28. Burakowski, T.; Wierzchoń, T. Inżynieria Powierzchni Metali; WNT: Warszawa, Poland, 1995.

29. Muteba, K.F.; Djouani, K.; Olwal, T. 5G NB-IoT: Design, Considerations, Solutions and Challenges. In Procedia Computer Science; Elsevier: Amsterdam, The Netherlands, 2021; pp. 86–93.