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Understanding Inconsistencies in Reported Relationships Between Vibration Frequency and Capacity Degradation of Lithium-Ion Batteries in Electric Vehicles

A Conceptual Framework Based on Structured Literature Review

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Abstract

The rapid growth of electric vehicles has increased the demand for reliable, durable lithium-ion battery systems. Mechanical vibration is an unavoidable operating condition for lithium-ion batteries used in electric vehicles. Nevertheless, its effect on capacity degradation remains insufficiently understood. Existing studies indicate that vibration can affect battery performance; however, reported findings remain inconsistent regarding critical vibration frequencies, the extent of degradation, the timing of performance loss, and whether measurable capacity loss occurs at all.

This thesis addresses these inconsistencies through a structured literature review aimed at explaining why existing research reports divergent findings on the relationship between mechanical vibration frequency and capacity degradation in lithium-ion batteries used in electric vehicles.

The findings suggest that vibration frequency alone does not sufficiently explain the variations in degradation behaviour reported across the literature. Instead, vibration-induced capacity degradation appears to be conditioned by several moderating factors, including the structural configuration of the battery cell, the timing of post-vibration performance assessment, the electrochemical state of charge during vibration exposure, and the severity of mechanical loading. Based on these findings, a conceptual framework is proposed to illustrate how these moderating factors shape the degradation outcomes reported across different experimental contexts in the literature.

The study concludes that the inconsistencies reported in the literature should be understood as variations arising from differences in battery characteristics and experimental approaches, rather than as direct contradictions. This thesis contributes to a clearer understanding of vibration-induced capacity degradation in lithium-ion batteries and provides a foundation for future empirical research that systematically examines these moderating conditions.

Keywords: *Lithium-ion battery, Mechanical vibration, Capacity degradation, Electric vehicles, Vibration frequency, Moderating factors, Structured literature review, Conceptual framework, State of charge, Mechanical loading severity*

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Table of Contents

1	Introduction.....	1
1.1	Problem Formulation	2
1.2	Purpose & Research Questions	4
1.3	Delimitations.....	5
2	Theoretical Background.....	6
2.1	Mechanical Vibration in Electric Vehicle Batteries	6
2.2	Vibration Effects on Lithium-Ion Battery.....	7
2.3	Experimental Evidence of Vibration-Induced Degradation	8
2.4	Capacity Degradation in Lithium-Ion Batteries	9
2.5	Frequency-Dependent Effects on Capacity Degradation in Li-ion Batteries	10
2.5.1	Reported Critical Frequencies.....	11
2.5.2	Reported Degradation Magnitudes	12
2.5.3	Timing of Observed Capacity Degradation	12
2.5.4	Occurrence of Capacity Degradation Under Vibration	13
2.6	Observed Patterns in Vibration Effects Across Studies	14
3	Methodology.....	17
3.1	Research Design.....	17
3.2	Structured Literature Review	18
3.3	Literature Search Strategy	19
3.4	Screening.....	22
3.5	Eligibility	22
3.6	Data Extraction and Analysis Approach	23
3.7	Conceptual Framework Development	24
3.8	Research Quality	24
3.9	Ethical Considerations.....	25
4	Result and Analysis.....	27
4.1	Moderating Factors in Vibration-Induced Capacity Degradation.....	27
4.2	Structural Configuration.....	27
4.3	Evaluation Timing	29
4.4	Electrochemical State of Charge	30
4.5	Mechanical Loading Severity.....	31

4.6	Conceptual Framework of Vibration-Induced Capacity Degradation	32
5	Discussion	34
5.1	Overview of Findings	34
5.2	Addressing the Research Questions	34
5.2.1	RQ1. What is the current state of research on the capacity degradation of lithium-ion batteries in electric vehicles due to mechanical vibration frequency?.....	34
5.2.2	RQ2. What inconsistencies exist between studies regarding critical vibration frequencies and capacity degradation magnitude in lithium-ion batteries?	35
5.2.3	RQ3. What moderating factors can explain why existing studies report inconsistent findings on the relationship between vibration frequency and capacity degradation in lithium-ion batteries?.....	36
6	Conclusion	37
6.1	Summary of Findings	37
6.2	Future Work.....	38
6.3	Final Remarks.....	38
	References	39

Table of Tables

Table 1. Key study areas used to define the literature search concepts	20
Table 2. Inclusion and Exclusion criteria.....	20
Table 3. Search keywords, search strings, and results	21

Table of Figures

Figure 1. Research design of the study	18
Figure 2. Structured Literature review process.....	19
Figure 3. Articles Included in the Study	23
Figure 4. Conceptual framework for explaining inconsistencies in the literature	33

List of Abbreviations

- EV : Electric Vehicle
- Li-ion : Lithium-ion
- LIB : Lithium-ion battery
- LIBs : Lithium-ion batteries
- NVH : Noise Vibration and Harshness
- SOC : State Of Charge
- SEI : Solid Electrolyte Interphase
- LLI : Loss of Lithium Inventory
- LAM : Loss of Active Material
- DOD : Depth Of Discharge
- EIS : Electrochemical Impedance Spectroscopy
- CT : Computed Tomography

1 Introduction

The electric vehicle (EV) market has grown rapidly over the past decade due to increasing environmental concerns, advancements in battery technology, and supportive government policies aimed at reducing carbon emissions. According to the International Energy Agency, total global EV sales exceeded seventeen million units in 2024, reflecting a sustained transition from internal combustion engines toward electrified passenger and commercial transport (IEA, 2025). As EV adoption continues to expand, expectations related to vehicle reliability, driving range, safety, and lifetime cost have become increasingly critical.

At the core of EV performance lies the Lithium-ion battery (LIB), which directly determines driving range, energy efficiency, safety, and long-term durability. Battery performance strongly influences vehicle usability and customer perception, making it one of the most critical subsystems in EVs (Zubi et al., 2018). As a result, maintaining battery health over the vehicle's lifetime is essential for both manufacturers and end users.

The importance of battery performance is clearly reflected in industry practices, as EV manufacturers commonly provide long-term battery warranties covering extended service periods, typically around eight years or high-mileage equivalents. These warranties often include minimum capacity retention requirements, indicating that capacity degradation is explicitly considered in product reliability and risk management strategies (Liu & Wang, 2025). The studies on EV ownership costs and battery lifetime assessment highlight that such warranty conditions are closely linked to manufacturer confidence in battery durability and are critical for ensuring customer acceptance and commercial viability of EVs (Hao et al., 2017).

One of the most significant challenges associated with LIBs is capacity degradation, defined as the progressive loss of usable energy storage capability over time (Birkl et al., 2017). Capacity degradation directly reduces driving range and contributes to user concerns such as range anxiety, which remains a major barrier to widespread EV adoption. Degraded battery capacity can increase perceived operating risk for consumers and negatively affect vehicle resale value, thereby impacting overall acceptance of electric vehicles (Tawfik et al., 2023).

In real automotive environments, EV batteries are subjected to complex mechanical loads arising from vehicle motion, road surface irregularities, suspension dynamics, and powertrain operation. These mechanical disturbances are part of the vehicle's noise, vibration, and harshness (NVH) characteristics and are transmitted to battery cells and modules through mounting structures and enclosures (Hooper et al., 2016; Qin et al., 2021). Because modern EV battery packs are structurally integrated into the vehicle body for stiffness and crash safety, vibrations generated at the road-tire interface propagate through the suspension and chassis into the battery enclosure. Consequently, battery cells are continuously exposed to structure-borne vibration during normal driving, making mechanical loading an unavoidable operating condition (Awan et al., 2025). The structural integration of EV battery packs within the vehicle chassis inherently subjects them to continuous structure-borne vibration during normal operation. Consequently, vibration exposure must be regarded as a fundamental operating condition when evaluating battery durability and performance.

To ensure mechanical durability and operational safety, LIBs for automotive applications are subjected to standardized vibration testing procedures, including SAE J2380 and UN 38.3. These standards prescribe vibration profiles intended to simulate mechanical conditions encountered during vehicle operation and are widely applied for battery qualification, certification, and transport approval (SAE International, 2021; United Nations Economic Commission for Europe [UNECE], 2023). However, such standards primarily serve as pass–fail durability tests and do not explicitly assess long-term performance-degradation mechanisms, such as capacity degradation under vibration loading.

Experimental studies have demonstrated that vibrational loading can influence LIB performance by accelerating capacity degradation, increasing internal resistance, and altering aging behaviour (Zhang et al., 2017; Aravind Reddy, 2025). Mechanical vibration can induce repeated dynamic loading and internal stress accumulation within battery components, potentially interacting with electrochemical aging processes and contributing to long-term performance deterioration. These findings indicate that vibration is not only a mechanical durability concern but also a factor influencing battery lifetime and usable energy.

Mechanical vibration is characterized by parameters such as amplitude, direction, duration, and frequency. Among these, vibration frequency is particularly significant because different frequency ranges can excite distinct mechanical responses within battery structures. Certain frequencies may amplify internal stresses or promote localized mechanical fatigue, thereby influencing how vibrational energy contributes to degradation processes within LIBs (Feng et al., 2017). As a result, vibration frequency plays a critical role in determining the severity and nature of vibration-induced capacity degradation.

1.1 Problem Formulation

While previous studies clearly demonstrate that mechanical vibration can influence LIB performance, the role of vibration frequency in capacity degradation remains poorly understood. Existing research has identified vibration frequency as a relevant parameter; however, reported outcomes vary widely in terms of critical frequency ranges, degradation magnitude, and timing of performance loss. As a result, the current body of literature provides valuable but fragmented evidence, making it difficult to draw consistent conclusions regarding frequency-dependent degradation behaviour. This lack of coherence highlights the need to move beyond isolated experimental observations and toward a structured interpretation of existing findings that systematically examines how variations in testing conditions, battery design, and evaluation methods influence reported vibration effects.

However, findings on vibration frequency-dependent degradation remain inconsistent across the literature, hindering the development of a unified understanding. Studies report that different vibration frequencies are most damaging to battery performance. For example, Wang et al. (2024) reported that batteries exposed to mid-range vibration at 50 Hz experienced the most severe degradation in cycling performance, whereas Zhang et al. (2018) found that low-frequency vibration at 5 Hz led to a noticeable reduction in battery discharge performance. These contrasting results indicate that damaging effects may occur across different frequency ranges rather than being confined to a single critical frequency.

In addition to disagreements regarding critical frequency, the reported magnitude of capacity degradation varies widely across studies. Wang et al. (2024) observed substantial capacity loss at 50 Hz, with degradation reaching 30.16%. In contrast, Zhang et al. (2018) and Zhang et al. (2017) reported only modest reductions in battery capacity following vibration exposure, with losses on the order of 0.2–0.3 Ah and an average decrease of approximately 68.8 mAh, respectively. By comparison, Hooper et al. (2016) found no statistically significant change in battery capacity despite applying vibration representative of long-term vehicle operation, underscoring the broad range of degradation magnitudes reported in the literature.

Differences are further observed in the timing of vibration-related degradation. Wang et al. (2024) showed that severe capacity loss became evident only after additional electrochemical cycling following vibration exposure. In contrast, Zhang et al. (2017) observed a reduction in capacity and an increase in internal resistance immediately after vibration testing. This difference indicates that vibration-induced damage may appear immediately or remain hidden, becoming apparent only during later battery operation.

Furthermore, some studies report substantial degradation under vibration loading, whereas others find no measurable capacity loss even under comparable or more severe conditions. Brand et al. (2015) reported no measurable capacity degradation despite observing internal structural damage, while Wang et al. (2024) identified both internal damage and significant capacity loss. Similarly, Hooper et al. (2017) found that realistic multi-directional vibration did not result in significant capacity degradation, although minor increases in internal resistance were detected. Together, these contrasting findings highlight the lack of consensus regarding whether mechanical vibration alone necessarily results in measurable capacity degradation in LIBs.

These substantial inconsistencies indicate that vibration frequency alone does not sufficiently explain the observed variations in capacity degradation reported across studies. The literature suggests that battery response to vibration is influenced by factors beyond frequency alone. For example, Awan et al. (2025) showed that battery cell format affects vibration response, with cylindrical cells exhibiting greater degradation than pouch cells under identical vibration conditions. Similarly, Berg et al. (2020) demonstrated that differences in internal cell design can significantly influence vulnerability to vibration-induced damage, even among cells of the same format. These findings imply that battery degradation under vibration is affected by multiple interacting aspects of testing conditions and cell construction rather than by vibration frequency in isolation.

Taken together, the observed differences in experimental approaches and battery designs suggest that vibration frequency alone may not act as an independent driver of capacity degradation. Instead, the impact of vibration frequency appears to depend on how vibration is applied and how battery performance is assessed across different studies. Consequently, the inconsistent findings reported in the literature may reflect variations in experimental configurations and evaluation practices, rather than fundamental disagreement about the role of vibration frequency itself.

Despite the growing number of studies examining vibration-induced degradation in LIBs, the mechanisms by which mechanical vibration affects battery electrical performance and safety remain unclear (Hua & Thomas, 2021). Most existing studies focus on specific test setups and report individual observations, rather than systematically integrating how variations in experimental conditions affect frequency-dependent degradation. As a result, it remains difficult to synthesize conflicting findings across studies and to develop a unified understanding of frequency-dependent vibration effects.

This lack of a moderating factor perspective limits the ability to integrate existing research into actionable knowledge and motivates the need for a structured analysis that identifies and proposes potential moderating factors through a comparative examination of the literature.

1.2 Purpose & Research Questions

This study aims to explain why existing research reports inconsistent findings on the relationship between mechanical vibration frequency and capacity degradation in lithium-ion batteries used in electric vehicles. While numerous experimental studies have investigated vibration-induced degradation, their findings vary considerably in terms of critical frequencies, degradation magnitude, and observed performance outcomes. By comparatively examining and integrating existing literature, this study seeks to connect these differences and develop a conceptual explanation for why such inconsistencies occur. The study contributes a **conceptual framework** that identifies and proposes **moderating factors** influencing how vibration frequency affects battery capacity degradation, thereby supporting clearer interpretation of prior findings and guiding future empirical research.

Research Questions

RQ1. What is the current state of research on the capacity degradation of lithium-ion batteries (LIBs) in electric vehicles due to mechanical vibration frequency?

This question examines existing studies to establish how vibration frequency effects on battery capacity have been investigated and reported in the literature.

RQ2. What inconsistencies exist between studies regarding critical vibration frequencies and capacity degradation magnitude in lithium-ion batteries (LIBs)?

This question focuses on identifying and synthesizing differences in reported critical frequencies and degradation outcomes across prior studies.

RQ3. What moderating factors can explain why existing studies report inconsistent findings on the relationship between vibration frequency and capacity degradation in lithium-ion batteries (LIBs)?

This question explores how differences in experimental conditions (such as acceleration level and state of charge), testing approaches, and battery characteristics may moderate reported vibration-induced degradation behaviour.

1.3 Delimitations

This study is limited to the examination of published literature between 2015 and 2025 that explores the effects of mechanical vibration frequency on capacity degradation in lithium-ion batteries used in electric vehicles. The scope is confined to lithium-ion battery technology, and other battery types and chemistries are not considered. The analysis focuses specifically on reported changes in battery capacity as the primary performance indicator, and the findings are specific to automotive electric vehicle applications and may not be directly applicable to other domains such as stationary energy storage or aerospace systems. Furthermore, this study focuses on mechanical vibration frequency and does not include studies that investigate electrical frequency effects on battery capacity degradation.

The scope of this thesis is confined to vibration-induced capacity degradation. Other forms of mechanical loading, such as crash impacts, shock events, or structural abuse conditions, are not considered. Electrochemical aging mechanisms are referenced only where relevant to understanding vibration-induced capacity degradation and are not examined as a standalone topic. Likewise, thermal runaway and battery safety failure are outside the scope of this study.

The conceptual framework proposed in this study is derived from a structured analysis of the selected literature and is based on four identified moderating factors. It is acknowledged that additional moderating factors may exist that were not captured within the reviewed studies. Furthermore, the framework is based on a limited selection of studies, and it should be understood as a conceptual foundation rather than a comprehensive or exhaustive explanation of all factors influencing vibration-induced capacity degradation. No experimental testing, numerical simulation, or statistical meta-analysis is conducted within this thesis, and the findings are intended to provide a foundation for future empirical investigation rather than experimental validation.

2 Theoretical Background

2.1 Mechanical Vibration in Electric Vehicle Batteries

Mechanical vibration refers to the oscillatory motion of a structure about its equilibrium position when subjected to dynamic excitation. In engineering systems, such motion arises from time-varying forces acting on the mass, stiffness, and damping properties of the structure. The dynamic response of a system depends on the relationship between the excitation characteristics and its inherent structural properties. When the excitation frequency approaches a structure's natural frequency, resonance may occur, potentially amplifying stresses and deformation (Ikeda et al., 2022).

In automotive applications, vibration is not an occasional disturbance but an inherent characteristic of normal vehicle operation. Even though electric vehicles eliminate combustion-related excitation sources, they remain continuously subjected to dynamic loads generated by road surface irregularities, tire-road interaction, suspension movement, drivetrain excitation, and structural coupling effects (Masri et al., 2024). The Study addressing NVH challenges in electric vehicles emphasizes that vibration remains a critical design consideration, highlighting that vibrational excitation is a persistent operational condition throughout the vehicle lifetime (Kurian et al., 2021). Consequently, vibration should be regarded as an unavoidable aspect of the electric vehicle operating environment.

Vibration generated during vehicle operation propagates through the structure as structure-borne excitation. Dynamic loads originating at the tire-road interface are transmitted through suspension components into the chassis and vehicle floor (Ghosh & Chatterjee, 2023). Because modern electric vehicle battery packs are structurally integrated within the vehicle body for packaging efficiency and structural rigidity, they are mechanically coupled to the chassis. Research on vibration-damping structures for battery pack casings demonstrates that externally induced dynamic excitation produces measurable vibrational response within the battery enclosure (Wei et al., 2025). Similarly, optimization studies on battery pack casing materials indicate that structural design influences vibration behaviour, further confirming that mechanical excitation from the vehicle structure is transferred into the battery pack (Zhang et al., 2019). Since lithium-ion (Li-ion) cells are mounted and constrained within this enclosure, vibrational motion of the casing results in dynamic mechanical loading of the internal cells. Thus, vibration reaches battery cells through structural transmission from the vehicle chassis to the battery pack and ultimately to the cell level.

Mechanical vibration in electric vehicles is characterized by several interrelated parameters that determine how dynamic loading is applied. Amplitude, commonly expressed as acceleration (g), represents the intensity of vibrational motion and influences the magnitude of stress within structural components. Frequency describes the rate of oscillation and plays a central role in dynamic response behaviour, particularly when excitation interacts with the system's natural frequencies. Direction refers to the axis along which vibration is applied (e.g., longitudinal, lateral, or vertical), affecting how loads are distributed within mechanically constrained assemblies. Duration reflects the time over which vibration is applied and may contribute to cumulative fatigue effects under prolonged exposure (Ghosh & Chatterjee, 2023).

In automotive testing environments, vibration may be applied either as sine excitation, typically used to study resonance behaviour, or as random vibration, which more closely represents broadband road-induced excitation conditions (Ghosh & Chatterjee, 2023; SAE International, 2021). Standardized procedures such as SAE J2380 and UN 38.3 specify frequency ranges, acceleration levels, excitation directions, and exposure durations to simulate mechanical conditions encountered during vehicle operation (SAE International, 2021; UNECE, 2023). These standards illustrate that vibration is inherently a multi-parameter loading condition rather than a single-variable input.

From this perspective, the mechanical influence of frequency should not be interpreted independently of other vibration parameters. The structural response to a given frequency may vary depending on the applied acceleration level, excitation direction, or exposure duration. Likewise, short-duration sine excitation may produce different dynamic behaviour compared to prolonged random vibration exposure. Therefore, variations in reported frequency-dependent degradation outcomes across studies may partly reflect differences in experimental configuration rather than the isolated effect of frequency alone. Examining vibration frequency within the broader mechanical context is thus necessary for a more consistent interpretation of its role in LIB capacity degradation.

2.2 Vibration Effects on Lithium-Ion Battery

Mechanical vibration has increasingly been recognized as a relevant operating stress factor for LIBs used in electric vehicles. Unlike isolated mechanical abuse events such as crush or impact, vibration introduces repeated cyclic loading throughout normal vehicle operation. Although the amplitude of such loading may be moderate, its continuous nature raises concerns regarding long-term structural integrity, electrical stability, and degradation behaviour of battery cells (Ghosh & Chatterjee, 2023; Hua & Thomas, 2021). These studies emphasize that vibration is an inherent component of vehicle operation and should be treated as a persistent mechanical stressor rather than an exceptional event.

Mechanical vibrations and shocks encountered during normal electric vehicle operation can affect LIBs by compromising their structural integrity and electrochemical stability, leading to capacity loss, performance degradation, and increased internal resistance (Sabeel et al., 2025). From a multi-physics perspective, vibration interacts simultaneously with the mechanical, electrical, and thermal domains of the cell (Shi et al., 2025; Du & Chen, 2022). Elevated resistance contributes to additional heat generation, and in severe cases, mechanically induced internal short circuits may occur. When such conditions persist, localized heating can escalate and, under unfavourable circumstances, trigger thermal runaway (Hua & Thomas, 2021). Therefore, thermal runaway may also be understood as a potential downstream consequence of sustained vibration-induced mechanical stress, particularly when combined with electrochemical cycling and high state-of-charge conditions.

Taken together, these findings indicate that vibration should not be viewed solely as a mechanical durability concern, but rather as a cumulative and condition-dependent stress factor capable of degrading structural integrity, destabilizing electrochemical performance, and increasing thermal risk over extended service life.

2.3 Experimental Evidence of Vibration-Induced Degradation

Experimental investigations demonstrate that vibrational loading can influence battery performance in multiple ways. Zhang et al. (2017) conducted vibration tests on Li-ion cells and observed measurable reductions in discharge performance and increases in internal resistance following exposure. Their statistical analysis indicated that vibration could alter electrical characteristics even when no structural damage is visible. Similarly, Zhang et al. (2018) reported that vibration coupled with temperature conditions affected discharge capacity and internal electrochemical behaviour, suggesting that mechanical excitation interacts with other operational stresses.

An Experimental investigation by Shukla et al., (2022) on LIBs under vibrational loading demonstrates that mechanical excitation alters the internal thermal field of the cell and affects its electrochemical stability. The study measured temperature distribution within batteries subjected to controlled vibration frequencies and amplitudes during discharge, revealing that vibration modifies internal heat generation patterns and can elevate localized temperatures under load. The experimental results indicate that dynamic mechanical excitation influences both thermal gradients and heat accumulation behaviour, particularly at higher discharge rates and specific vibration conditions. This suggests that vibration does not merely act as an external mechanical disturbance but interacts with electrochemical processes to alter thermal response. These findings imply that vibration-induced temperature variations may accelerate aging mechanisms and increase safety risk by promoting uneven heat distribution within the cell, thereby reinforcing the multi-physics nature of vibration-induced degradation.

Beyond capacity loss, studies have also consistently reported increases in internal resistance following vibration exposure. Hooper et al. (2016) found that cylindrical NMC cells subjected to automotive representative vibration profiles exhibited minor but measurable impedance growth, even in the absence of significant capacity fade. Brand et al. (2015) similarly reported structural changes and variations in electrical resistance after vibration and shock testing. Somerville et al. (2017) demonstrated that vibration-induced mechanical stress destabilized the Solid Electrolyte Interphase (SEI) surface film on electrode materials, compromising its protective function and thereby accelerating electrochemical degradation. Collectively, these findings show that vibration-induced degradation may become evident through changes in electrical parameters, even when substantial capacity loss has not yet been observed.

Although the literature reports both capacity variation and resistance growth under vibration exposure, the magnitude and manifestation of these effects remain inconsistent across experimental configurations. Among the various degradation indicators, capacity loss represents the most direct and practically relevant measure of battery performance deterioration, as it directly affects driving range, warranty thresholds, and user perception. Therefore, while acknowledging the broader structural and electrical impacts of vibration, this thesis specifically focuses on vibration-induced capacity degradation as the primary metric for evaluating battery performance under mechanical excitation.

2.4 Capacity Degradation in Lithium-Ion Batteries

Capacity degradation, also referred to as capacity fade, represents the progressive reduction in the usable charge storage capability of a LIB over time. It is typically quantified as the decrease in discharge capacity relative to the battery's initial rated capacity and is widely regarded as a primary indicator of battery aging and state of health. This decline in capacity arises from irreversible internal aging processes within the cell, including the consumption of active lithium and structural changes that increase internal resistance (Zhou & Bao, 2021; Timilsina et al., 2023). In practical terms, capacity degradation reflects the extent to which a battery can no longer deliver its originally designed energy output under normal operating conditions. As degradation progresses, the available energy output decreases, directly reducing driving range and performance in electric vehicle applications (Guo et al., 2021).

Capacity degradation in lithium-ion batteries results from progressive internal aging mechanisms that reduce lithium availability and the effective amount of active electrode material. Rather than arising from a single failure pathway, capacity fade reflects the combined outcome of multiple interacting processes within the cell. These mechanisms are commonly categorized as loss of lithium inventory (LLI), loss of active material (LAM), and increased internal resistance, all of which directly contribute to reduced discharge capacity and overall electrochemical performance (Han et al., 2019; Madani et al., 2025). These categories are also linked to physical changes within the electrodes, where ongoing degradation can intensify lithium loss and resistance growth. Accordingly, capacity degradation should be understood as the result of interacting electrochemical, structural, and interfacial changes that develop within the battery over time. Importantly, these degradation processes are influenced not only by internal electrochemical reactions but also by external mechanical stresses, which can intensify structural damage, destabilize electrode interfaces, and accelerate impedance growth (Liu et al., 2025; Shi et al., 2024). Therefore, capacity loss should be understood as the result of interacting internal mechanisms that may be further amplified under specific operating or mechanical loading conditions.

Battery degradation is influenced by several external operating conditions, including temperature, current rate, and depth of discharge (Alipour et al., 2020). Among these, temperature is widely recognized as a dominant factor affecting battery aging behaviour and capacity retention. Both elevated and low operating temperatures can accelerate degradation processes and contribute to capacity fade by intensifying side reactions and altering internal electrochemical stability (Alipour et al., 2020; Carnovale & Li, 2020). This indicates that capacity degradation is not solely determined by intrinsic material properties but is strongly shaped by the thermal environment in which the battery operates. Therefore, maintaining appropriate operating temperatures is critical for controlling long-term performance decline in electric vehicle applications.

In addition to temperature effects, battery ageing is also strongly influenced by electrochemical operating conditions. The state of charge (SOC) is another critical operating parameter that influences LIB ageing. Operating at high SOC levels accelerates dependent side reactions and degradation processes that increase capacity loss over time, whereas extremely low SOC conditions can induce structural instability, including copper dissolution and dendrite formation, thereby shortening battery lifespan (Madani et al., 2025; Guo et al., 2021). These effects show that battery degradation is sensitive not only to environmental factor such as

temperature, but also to the electrochemical state at which the battery is maintained or cycled. Consequently, ageing behaviour depends strongly on charge management strategies during both storage and operation.

Beyond temperature and SOC effects, the charge and discharge rate (C-rate) represents another significant operational parameter influencing capacity degradation in LIBs. Higher C-rates accelerate aging processes and result in more pronounced capacity loss over time (Madani et al., 2025). As the charge-discharge rate increases, electrochemical reactions proceed more rapidly and internal stresses within the cell intensify, accelerating capacity attenuation (Zeng & Liu, 2023). Aggressive charging or high-power operating conditions, therefore, amplify degradation mechanisms and reduce long-term battery durability. Careful control of charging and discharging rates is thus important for extending cycle life and mitigating capacity fade.

In addition to C-rate effects, depth of discharge (DOD) also plays a significant role in LIB degradation. Experimental evidence indicates that batteries cycled within moderate discharge ranges experience relatively limited capacity loss and smaller increases in internal resistance over repeated cycles, whereas deeper discharge conditions accelerate aging processes and amplify degradation effects (Zeng & Liu, 2023; Zhu et al., 2024). The extent to which a battery is repeatedly discharged therefore, influences the mechanical and electrochemical stress imposed on electrode materials. Managing discharge depth is consequently an important strategy for mitigating long-term capacity fade and preserving battery durability.

Overall, capacity degradation in LIBs is governed by the interaction of internal aging mechanisms and external operating conditions. While intrinsic processes such as loss of lithium inventory, loss of active material, and resistance growth determine the fundamental limits of performance, operational factors including temperature, state-of-charge, charge–discharge rate, and depth of discharge significantly influence the rate at which these mechanisms progress. This indicates that capacity fade is not a fixed material property, but a dynamic outcome shaped by how the battery is operated and the conditions to which it is exposed. Consequently, a comprehensive understanding of capacity degradation requires consideration of external stress factors that collectively determine long-term battery behaviour.

2.5 Frequency-Dependent Effects on Capacity Degradation in Li-ion Batteries

Mechanical vibration is characterized by multiple parameters, including frequency, acceleration amplitude, exposure duration, and loading profile (Hooper et al., 2016). While each of these variables may influence battery performance, this section focuses specifically on vibration frequency and its relationship to capacity degradation. Capacity fade is widely used as a primary indicator of battery health and long-term performance, and it serves as a central outcome variable in experimental vibration studies (Wang et al., 2024; Li et al., 2025; Awan et al., 2025). However, a review of the literature reveals divergent findings regarding the role of frequency. Studies report different frequency ranges as most damaging, and their findings vary in degradation magnitude, timing, and even in whether measurable performance loss is observed.

2.5.1 Reported Critical Frequencies

In the context of vibration studies, a critical frequency refers to a frequency range at which vibration exposure is associated with comparatively greater performance degradation than other tested frequencies. Experimental investigations have examined a wide range of vibration frequencies, and the frequency bands identified as most influential vary across studies. Some studies report stronger degradation effects at lower frequencies. For example, Zhang et al. (2018) observed that vibration in the 5–30 Hz range resulted in more pronounced performance deterioration compared to frequencies above 40 Hz, suggesting increased sensitivity within this lower frequency band.

In contrast, other studies indicate greater sensitivity at mid-range frequencies. Wang et al. (2024) tested discrete frequencies of 20 Hz, 50 Hz, and 75 Hz and observed the highest degradation at 50 Hz, suggesting a mid-frequency effect based on comparative results. Similarly, Li et al. (2025) subjected cells to continuous vibration at 35 Hz and reported significantly greater capacity loss than non-vibrated cells. However, because only a single frequency was examined, this result demonstrates that vibration at 35 Hz can be damaging but does not establish it as uniquely critical relative to other frequencies.

Broad-range vibration protocols further complicate interpretation. Standardized procedures such as UN 38.3 and SAE J2380 apply frequency sweeps across wide bands (e.g., 10–190 Hz or 1–600 Hz) (Hooper et al., 2016; Omariba et al., 2020), exposing cells to multiple frequencies simultaneously and limiting the ability to isolate specific damaging bands. Jones et al. (2023), performing in-operando testing under UN 38.3 conditions, reported no significant difference in capacity degradation between 18 Hz and 36 Hz when combined with additional abuse stressors. Similarly, Berg et al. (2020) observed no measurable capacity or impedance degradation in 18650 Li-ion cells subjected to standard SAE J2380 random vibration loading (validated up to approximately 200 Hz), despite detailed evaluation using computed tomography (CT) imaging, electrochemical impedance spectroscopy (EIS), and capacity measurements. In a multi-axis six-degree-of-freedom vibration study, Pop et al. (2025) also reported no significant degradation under standard SAE J2380 conditions, with performance deterioration emerging only under intensified or upscaled vibration profiles. These findings indicate that, under standardized qualification profiles, vibration exposure does not consistently produce detectable electrochemical degradation, and frequency-specific effects may be difficult to isolate within such testing frameworks.

Taken together, the literature does not converge on a single critical vibration frequency. Reported sensitivity ranges span low, mid, and broad frequency bands, suggesting that frequency-dependent degradation may be context-dependent rather than universally attributable to a specific frequency band.

2.5.2 Reported Degradation Magnitudes

Reported degradation magnitudes under vibration vary across experimental studies. In some investigations, substantial capacity loss has been observed. For example, Wang et al. (2024) reported capacity fade exceeding 30% at 50 Hz following subsequent electrochemical cycling, while Li et al. (2025) documented higher degradation in vibrated cells compared to non-vibrated controls at 35 Hz. These observations indicate that, under certain testing configurations, vibration exposure is associated with pronounced reductions in electrochemical performance.

Smaller capacity reductions have also been observed in several studies. Awan et al. (2025) reported capacity fades between 4% and 10% depending on the vibration axis, while Lee et al. (2021) found a reduction of about 2% under a railway vibration profile. Zhang et al. (2018) recorded an absolute decrease of 0.2–0.3 Ah under low-frequency vibration, although direct comparison with other studies is difficult because different reporting methods were used. In other cases, little or no measurable capacity loss was found. Caposciutti et al. (2020), Jones et al. (2023), and Li et al. (2019) observed minimal degradation when vibration was applied alone.

Overall, the reported degradation magnitudes vary considerably across studies. This suggests that vibration frequency alone does not reliably determine the severity of capacity fade, and that the level of degradation depends on the specific testing conditions applied in each investigation.

2.5.3 Timing of Observed Capacity Degradation

The timing at which capacity degradation is evaluated varies across vibration studies, and this variation appears to influence the reported outcomes. Not all investigations assess battery performance at the same stage of testing, which affects whether degradation is immediately visible or only detected later.

Some studies report measurable performance changes immediately after vibration exposure. For example, Awan et al. (2025), Bruen et al. (2016), and Bisht et al. (2024) observed reductions in discharge capacity and increases in internal resistance directly following vibration testing. In these cases, degradation was identified without the need for additional cycling, suggesting that vibration alone was sufficient to produce detectable performance changes.

In other studies, degradation becomes apparent only during subsequent electrochemical cycling. Wang et al. (2024) found no significant capacity loss immediately after vibration, but substantial fade developed during later cycling. Similarly, Li et al. (2025) reported only minor immediate changes, while long-term cycling revealed accelerated degradation in vibrated cells. These findings indicate that vibration may introduce internal damage that is not instantly reflected in capacity measurements but becomes more pronounced during continued battery operation.

Other studies report minimal or even slightly improved performance under certain vibration conditions. Ryu et al. (2025) observed improved capacity retention under low-frequency vibration, and Mocera et al. (2020) reported only limited progressive reduction during prolonged exposure. These results further highlight that degradation is not always immediate or clearly detectable under all testing approaches.

Overall, the point at which capacity is evaluated immediately after vibration, during exposure, or after extended cycling plays an important role in shaping reported conclusions. Differences in evaluation timing may therefore contribute to variation in findings across studies.

2.5.4 Occurrence of Capacity Degradation Under Vibration

The presence of measurable capacity degradation under vibration is not consistently reported across studies. While some investigations identify clear performance loss, others report minimal or no detectable change under similar vibration conditions.

Several studies report noticeable degradation in vibrated cells compared to non-vibrated controls. Wang et al. (2024) and Li et al. (2025) observed significant capacity fade and increased resistance following vibration exposure, particularly when combined with subsequent cycling. Awan et al. (2025) also reported measurable reductions in discharge capacity under axis-specific vibration loading. In these cases, vibration was associated with observable electrochemical performance decline.

In contrast, other investigations found little or no statistically significant capacity loss when vibration was applied alone. Caposciutti et al. (2021) reported no significant difference between vibrating and non-vibrating cells across the tested frequency range. Similarly, Jones et al. (2023) did not detect significant variation in capacity under UN 38.3 vibration conditions combined with other stressors. Li et al. (2019) and Mocera et al. (2020) also observed minimal or limited degradation under their respective testing conditions.

These contrasting findings indicate that measurable capacity degradation under vibration is not uniformly observed in vibration studies. The presence or absence of detectable performance loss varies depending on the specific experimental conditions and evaluation approaches used.

The reviewed literature demonstrates substantial inconsistency in reported frequency-dependent degradation effects. Studies disagree not only on which frequency ranges are most damaging, but also on the magnitude of capacity fade, the timing of performance deterioration, and even the occurrence of measurable degradation under vibration. These differences cannot be explained by vibration frequency alone. Instead, variations in experimental design, vibration protocols, cell configuration, and performance evaluation methods appear to shape the reported outcomes. This suggests that a closer examination of these contextual factors is necessary to better understand why results differ across studies.

2.6 Observed Patterns in Vibration Effects Across Studies

The inconsistencies identified in the frequency-dependent vibration literature suggest that vibration frequency alone is insufficient to explain degradation behaviour. Studies diverge not only in reported critical frequency ranges but also in degradation magnitude, timing, and even in whether measurable capacity fade occurs at all. Such variability indicates that additional contextual factors shape degradation responses, yet these factors are not consistently controlled or reported across investigations. Differences in mechanical loading severity, electrochemical state during testing, evaluation timing, vibration methodology, and cell configuration appear to significantly influence experimental outcomes.

Mechanical loading severity represents one of the most structurally important sources of variation. Applied acceleration levels vary considerably across studies, from standardized automotive qualification profiles to intensified laboratory protocols applying substantially higher loading amplitudes (Hooper et al., 2016; Li et al., 2025). Studies employing high acceleration and prolonged exposure consistently report more pronounced degradation. For instance, Li et al. (2025) identified an acceleration-dependent threshold beyond which capacity fade and resistance growth emerged rapidly under 36 g loading sustained for 200 hours. Similarly, Reddy et al. (2025) reported that increased vibration intensity accelerated electrochemical degradation, highlighting the sensitivity of cell performance to mechanical loading amplitude. Beyond continuous vibration, dynamic mechanical shocks have also been shown to accelerate degradation. Adams et al. (2018) demonstrated that increasing the number of impact cycles significantly reduced Coulombic efficiency, increased charge-transfer resistance, and accelerated long-term capacity fading, linking accumulated mechanical stress to electrochemical performance decay. In contrast, investigations conducted under standardized SAE J2380 conditions reported measurable but comparatively moderate performance deterioration (Somerville et al., 2017; Hooper et al., 2016). Similarly, Bruen et al. (2016), applying SAE J2380 random vibration representative of long-term vehicle operation, observed notable increases in ohmic resistance and measurable capacity reduction, with degradation severity varying according to loading orientation. Other studies using short-duration excitation or moderate fatigue loading observed minimal or statistically insignificant effects (Caposciutti et al., 2021; Mouravieff et al., 2020). Brand et al. (2015) further demonstrated that standardized UN 38.3 vibration conditions (maximum 8 g) produced no measurable capacity loss, whereas intensified sweep sine excitation led to internal structural damage and increased internal resistance, despite similar frequency ranges. The absence of standardized loading protocols across studies, therefore, complicates cross-comparison and may lead to misleading interpretations of frequency sensitivity when severity effects are not explicitly considered.

The electrochemical state of the battery during vibration exposure introduces additional variability in reported degradation behaviour. Some studies examine multiple SOC levels under vibration, as SOC influences mechanical and interfacial stability. Li et al. (2025) demonstrated that higher SOC significantly amplified capacity fade and resistance increase under identical mechanical conditions. This suggests that degradation behaviour under vibration may vary with electrochemical conditions. In contrast, several studies apply vibration at a fixed intermediate SOC, often around 50%, without assessing SOC sensitivity (Somerville et al., 2017; Hooper et al., 2016). Other studies reporting minimal degradation similarly do not emphasize SOC as an experimental variable (Caposciutti et al., 2021; Mouravieff et al., 2020), which may partially explain differences in reported degradation severity across studies. Structural vibration studies

further indicate that SOC alters internal stiffness and natural frequency, suggesting that vibration response may vary with electrochemical condition (Eidnejad et al., 2025; Sonnberger et al., 2022). This implies that identical excitation frequencies could interact differently with cells depending on their charge state. Berg et al. (2020) examined 18650 cells at 25%, 50%, and 75% SOC under random vibration according to SAE J2380, as well as at 0% SOC under a more severe profile. While no significant electrical degradation was observed across SOC levels under standard automotive conditions, the systematic consideration of multiple SOC states indicates that electrochemical conditions can influence vibration response and remain inconsistently controlled across the literature. Collectively, these findings suggest that SOC may function as a conditioning factor in vibration-induced degradation, contributing to variability in reported outcomes.

Differences in evaluation timing further influence reported degradation outcomes across vibration studies. Some investigations assess battery performance immediately after vibration exposure (Somerville et al., 2017; Zhang et al., 2017; Awan et al., 2025), capturing short-term changes in discharge capacity or internal resistance measured directly after excitation. Others evaluate battery behaviour during vibration itself; for example, Zhang et al. (2018) monitored discharge performance under sine dwell excitation, recording electrochemical responses in operando. While this approach reflects the immediate combined effect of mechanical disturbance and electrochemical response, it may not clearly separate temporary fluctuations from permanent structural damage. In contrast, several studies examine degradation only after vibration, followed by subsequent electrochemical cycling. Wang et al. (2024) and Li et al. (2025) reported that vibrated cells experienced significantly greater capacity fade during later cycling compared to non-vibrated controls. Wang et al. (2024), for instance, observed substantial additional degradation after 100 post-vibration cycles despite relatively minor immediate changes. Similarly, Adams et al. (2018) linked mechanical impact exposure to progressive increases in charge-transfer resistance and long-term performance decline, suggesting that vibration-induced defects may develop gradually during continued operation. These findings indicate that vibration can introduce latent structural or interfacial damage that is not immediately detectable but becomes more pronounced during cycling. As a result, the reported severity of vibration-induced degradation depends not only on mechanical conditions but also on when performance is evaluated, a point also noted in recent synthesis work on vibration impacts in lithium-ion batteries (Reddy, 2025). Without consistent evaluation protocols, the apparent severity of vibration-induced degradation may therefore reflect measurement timing rather than intrinsic frequency effects.

Finally, methodological and structural differences further complicate the interpretation of vibration-induced degradation. Experimental protocols vary between single-frequency sinusoidal excitation (Li et al., 2025; Caposciutti et al., 2021) and broadband random multi-axis loading under standardized profiles (Hooper et al., 2016; Somerville et al., 2017), introducing methodological variability in how mechanical stresses are applied and transmitted within the cell. In addition, LIBs are manufactured in cylindrical, prismatic, and pouch configurations, each with distinct mechanical characteristics that influence their response to vibration (Rojas & Khan, 2022). Cylindrical cells typically contain a wound jelly-roll electrode structure enclosed within a rigid metal casing and often supported by a central mandrel, whereas pouch cells employ stacked electrodes within a flexible laminated enclosure (Lu et al., 2017). Comparative investigations have shown that these design differences influence

mechanical sensitivity under vibration, with cylindrical cells generally exhibiting greater susceptibility to structural damage than pouch and prismatic formats (Brand et al., 2015; Awan et al., 2025). Beyond format-level distinctions, internal architectural features further modify mechanical response. For example, Berg et al. (2020) demonstrated that variations in mandrel diameter and internal clearances among 18650 cylindrical cells significantly influenced damage development under random vibration loading, where cells with lower mandrel-to-jelly-roll ratios exhibited localized tab damage despite identical external excitation. Similarly, Parasumanna et al. (2019) reported stiffness changes and microstructural variations within large-format cylindrical cells following mechanical abuse, indicating that stress distribution within the cell is geometry-dependent. Structural variability is also evident at the module and pack level. Park et al. (2020) observed that multi-axis excitation and installation orientation influenced the electrical response of battery packs under simulated seismic conditions, suggesting that mounting direction and boundary conditions may further affect vibration sensitivity. Taken together, these observations indicate that vibration response is shaped not only by external loading conditions but also by structural configuration. Consequently, structural heterogeneity across studies may contribute to variations in reported degradation severity even when vibration profiles appear comparable.

Overall, these observations suggest that vibration-induced capacity degradation is unlikely to be governed by frequency alone. Instead, battery responses may depend on a set of contextual factors, including the intensity of mechanical loading, the electrochemical state, the timing of evaluations, and the cell's internal structure. Since these factors have not been systematically examined together, the apparent differences between studies may reflect variations in experimental conditions rather than true contradictions in the underlying physical behaviour, highlighting the need for a more integrated theoretical understanding of vibration-induced capacity degradation. A more structured conceptual approach is therefore needed to better understand the conditions under which vibration exposure leads to significant capacity loss.

3 Methodology

This chapter describes the methodological approach used in this study to examine vibration-induced capacity degradation in LIBs used in electric vehicles. This explains the research design and the procedures followed to collect, screen, and analyse the relevant literature. The chapter outlines the structured literature review process, including the search strategy, inclusion and exclusion criteria, and the steps for identifying and selecting the most relevant studies. It also explains the approach used to examine the selected papers and interpret the findings. Finally, the chapter describes how the insights derived from the literature analysis were used to develop the conceptual framework presented in the subsequent chapter.

3.1 Research Design

To better understand how vibration frequency influences capacity degradation in LIBs used in electric vehicles, it is necessary to carefully examine and interpret existing research in this field. Since this study does not involve conducting new laboratory experiments, it relies on analysing previously published studies. Therefore, the research follows a qualitative and literature-based approach.

This type of study focuses on interpreting findings, comparing results across different experiments, and identifying patterns in the literature. Qualitative literature research is particularly suitable when the aim is to explore inconsistencies and develop theoretical explanations rather than measure numerical relationships directly (Creswell, 2016).

A structured literature review method was adopted to ensure that the literature selection and analysis were carried out in a systematic and transparent manner. Structured reviews help organize existing knowledge, identify research gaps, and build conceptual understanding in emerging or complex research areas (Snyder, 2019). In this thesis, the review is analytical rather than statistical and compares contextual differences across studies to explain why findings vary.

Three research questions guide this study. The first research question (RQ1) examines the current state of research on vibration-induced capacity degradation. The second research question (RQ2) identifies inconsistencies in reported frequencies and degradation magnitudes. The third research question (RQ3) builds on these findings to propose a conceptual framework that explains how contextual moderating factors are reported in different studies. The integration of findings from RQ1 and RQ2 forms the basis for the conceptual framework developed in this study, as illustrated in figure 1.

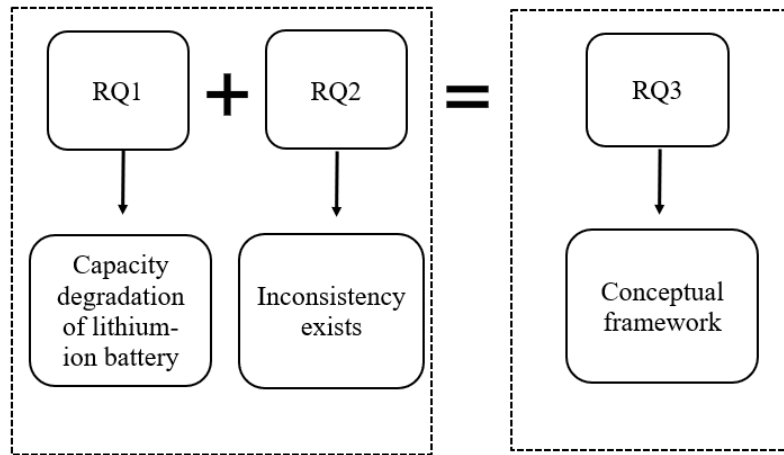


Figure 1. Research design of the study

3.2 Structured Literature Review

A literature review summarizes existing knowledge, offering insights into relevant theories, methods, and areas for advancement in current research. It goes beyond merely collecting sources; it involves analyzing, synthesizing, and critically evaluating them to provide a comprehensive understanding of the subject. A well-executed literature review highlights the researcher's familiarity with the topic and its scientific context, establishes a conceptual and methodological framework, and highlights how the study contributes to addressing research gaps or advancing the field (Snyder, 2019).

According to Säfsten and Gustavsson (2020), carrying out a structured literature review requires a defined sequence and consists of ten phases. These guidelines provide a step-by-step approach for searching, selecting, and analysing relevant research articles

The review process involved several stages (Figure 2). First, search keywords and databases were defined to identify relevant studies related to lithium-ion batteries, mechanical vibration, and capacity degradation. Next, the collected studies were screened using inclusion and exclusion criteria to ensure that only relevant research was considered. The selected papers were then reviewed in detail, and important information such as vibration parameters, testing conditions, and reported capacity degradation results was extracted.

Using this structured process helps ensure that the literature review is conducted in a transparent and systematic way, while also reducing bias in the selection of studies. The overall steps followed in this literature review process, based on the approaches suggested by Säfsten and Gustavsson (2020) and Booth et al. (2021), are illustrated in the flow diagram shown in figure 2.

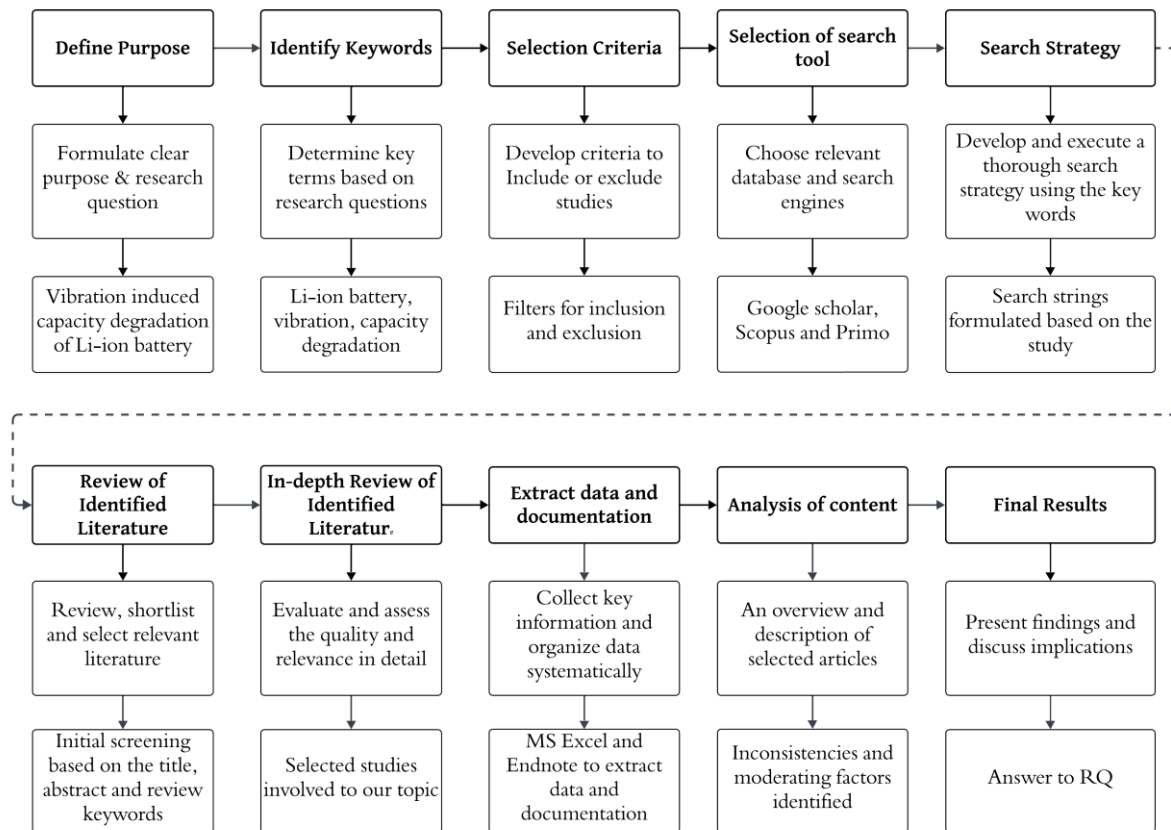


Figure 2. Structured Literature review process

3.3 Literature Search Strategy

The search for relevant literature began with the use of Scopus and Primo, focusing on keywords. Boolean operators such as AND, OR, and NOT were used together with the keywords to refine the search process. These searches returned a wide range of relevant studies, which were further filtered by citation relevance and publication quality to identify the most relevant research articles and journals. The snowball technique identifies additional literature through references in selected papers. Backward snowballing focuses on reviewing cited references (Wohlin, C., 2014).

Selection criteria were applied based on the relevance of the titles, abstracts and keywords with the most suitable articles were shortlisted and saved using EndNote and MS Excel software. The content of selected articles, focusing on abstracts, analysis, and conclusions, was examined to extract relevant information and identify key concepts. Additionally, books were utilized for literature study through online resources and university libraries.

Table 1. Key study areas used to define the literature search concepts

Study Field	Categories
Lithium-ion batteries in EV	Battery chemistry and cell structure; Battery performance and degradation mechanisms; EV battery management systems
Vibration effects on Lithium-ion batteries	Sources of vibration in electric vehicles; Mechanical stress and structural effects on cells; Experimental vibration testing methods
Capacity degradation in Lithium-ion battery	Mechanisms of capacity fade; Influence of mechanical stress on degradation; Experimental observations of capacity loss; Factors influencing degradation under vibration

Inclusion and exclusion criteria were defined to narrow down the search results and ensure relevance (Table 2). These criteria helped identify studies specifically related to

Table 2. Inclusion and Exclusion criteria

Criteria	Inclusion	Exclusion
Keyword Relevance	Studies containing keywords that are closely related to the research topic	Studies that do not include keywords relevant to the research focus.
Publication Period	Studies published between 2015 and 2025.	Studies published before 2015 or after 2025, except for a few highly significant references.
Language	Publications written in English.	Publications written in languages other than English.
Document Category	Journal articles, conference papers, book chapters, review papers and academic books.	Dissertations, theses, patents, technical reports.
Source Type	Credible academic sources such as journal publications, conference proceedings, book series, and scholarly books.	Grey literature, unpublished materials, or sources lacking academic reliability.

The search strategy was carefully structured to achieve broad coverage of the relevant literature while maintaining a focus on the key areas of the study (Säfsten & Gustavsson, 2020; Booth et al., 2021). Although the initial search gave many results, a systematic screening and refinement procedure was applied to identify the most relevant studies. The following steps were undertaken during this process:

1. Screening of Titles and Abstracts:

In the first stage, the titles and abstracts of the retrieved publications were examined to determine their relevance to the research objectives.

2. Refinement of Keywords:

The search terms were progressively refined to improve the precision of the search and to ensure that the retrieved studies were closely aligned with the research questions.

3. Application of Inclusion and Exclusion Criteria:

Predefined inclusion and exclusion criteria were used to filter the identified literature, selecting studies that provide meaningful insights into vibration effects, mechanical loading conditions, and capacity degradation in LIBs.

4. Snowballing Method:

In addition, a snowballing approach was adopted by examining the reference lists of key articles to identify additional relevant publications and to enhance the overall coverage of the literature (Wohlin, C., 2014).

Table 3 shows the list of keywords and the corresponding search results after applying the inclusion and exclusion criteria.

Table 3. Search keywords, search strings, and results

Keywords	Search Platform	Hits
Vibration AND Frequency AND Lithium-ion battery	Primo	121
Vibration effects lithium-ion battery	Primo	203
Vibration induced battery degradation	Scopus	13
("lithium-ion battery" OR "Li-ion battery" OR "lithium battery") AND ("capacity degradation" OR "capacity fade" OR "aging mechanism" OR "battery aging" OR "battery degradation" OR "degradation mechanism") AND ("electric vehicle" OR "automotive" OR "state of health" OR "temperature" OR "internal resistance" OR "electrochemical")	Scopus	62
("lithium-ion battery" OR "Li-ion battery" OR "lithium battery") AND ("vibration" OR "mechanical vibration" OR "random vibration" OR "vibration durability" OR "vibration testing" OR "vibration test" OR "vibration load" OR "vibration exposure") AND ("capacity fade" OR "capacity degradation" OR "degradation" OR "aging" OR "battery performance" OR "cycling" OR "temperature" OR "SEI")	Scopus	253
"lithium-ion battery" OR "Li-ion battery" OR "lithium battery") AND ("vibration" OR	Scopus	163

<p>"mechanical vibration" OR "random vibration" OR "vibration durability" OR "vibration testing" OR "vibration stress" OR "vibration aged" OR "shocks" OR "dynamic impact") AND ("capacity fade" OR "aging mechanism" OR "degradation" OR "performance degradation" OR "mechanical performance" OR "cell design" OR "battery pack" OR "electrical characteristics" OR "electrodes" OR "temperature" OR "battery management system" OR "BMS"</p>		
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3.4 Screening

The collected literature was carefully examined during the screening stage to determine its suitability for inclusion in the study. This stage involved multiple steps to ensure that only relevant and reliable sources were considered for the final analysis. Initially, the titles, abstracts, and keywords of the identified publications were reviewed to evaluate their relevance to the research objectives. Studies that did not meet the predefined inclusion criteria, such as those lacking relevant keywords or falling outside the selected publication period, were excluded at this stage. This preliminary screening helped refine the selection process by reducing the number of articles to those most relevant to the research topic (Säfsten & Gustavsson, 2020; Booth et al., 2021).

3.5 Eligibility

After the preliminary screening, the remaining literature was subjected to a more comprehensive assessment to determine its suitability for inclusion in the study. At this stage, the full text of each publication was carefully reviewed to evaluate its relevance and quality in relation to the research questions and objectives. Studies that did not satisfy the predefined inclusion criteria or were considered to lack sufficient relevance or academic credibility were excluded from further analysis. This detailed evaluation ensured that only reliable and relevant sources were retained for the final review, thereby strengthening the validity and reliability of the study findings (Säfsten & Gustavsson, 2020; Booth et al., 2021).

The initial search began with 128 articles that were identified and saved using EndNote. The articles were studied carefully, focusing on the title, abstract, and analysis. Notes were recorded for each selected article in MS Excel, highlighting the main findings and relevant information related to vibration-induced capacity degradation in LIBs. These notes helped organize the literature and supported the comparison of studies during the analysis stage. After completing the screening and eligibility assessment, a total of 34 articles were included in this study. The overall selection process is illustrated in figure 3.

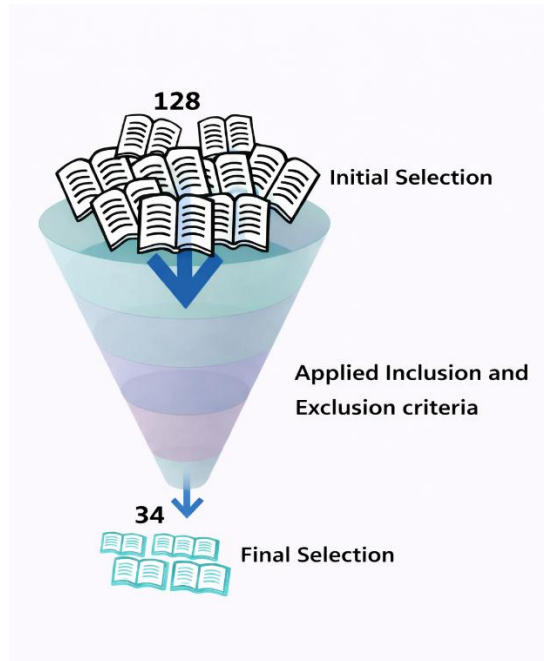


Figure 3. Articles Included in the Study

3.6 Data Extraction and Analysis Approach

After the final set of studies was selected, each paper was carefully reviewed to extract relevant information related to vibration-induced capacity degradation in lithium-ion batteries. The extracted information was organized to allow a comparison of the findings reported across the selected studies.

The analysis was conducted using a structured interpretive approach aimed at identifying and explaining differences in the results reported in the literature. First, patterns in the findings were identified by comparing how different studies reported capacity degradation behaviour under vibration conditions. This step helped reveal areas where studies showed agreement as well as where their findings differed.

Once these patterns were identified, the analysis examined why these variations may be important for understanding vibration-related capacity degradation. The literature was then reviewed more closely to explore possible explanations discussed by previous researchers, particularly those related to the interaction between mechanical loading and battery degradation.

Following this, the findings were interpreted in relation to the broader experimental context described in the selected studies. This interpretive step helped provide a deeper understanding of how differences in research conditions may influence the reported outcomes.

Finally, based on the insights obtained from this step-by-step analysis, analytical propositions were developed to summarize the key interpretations derived from the literature. In this way, the analysis moves beyond simply summarizing previous studies and instead develops interpretations grounded in the existing body of research. These interpretations form the basis for the conceptual explanations presented in the following chapter.

3.7 Conceptual Framework Development

This section explains how the conceptual framework presented in this thesis was developed. The framework was created to provide a clear and structured way of understanding the differences reported in previous studies on vibration-induced capacity degradation in lithium-ion batteries used in electric vehicles. The development of the framework began with a detailed review of the selected studies during the analysis phase.

The findings from the literature were compared to understand how vibration-related capacity degradation has been reported across different studies. This comparison helped highlight similarities and differences in the reported results and made it possible to identify inconsistencies across the literature.

After identifying these inconsistencies, the findings were further examined in relation to the conditions under which the studies were conducted. This helped in understanding how differences in research conditions may be linked to the variation in results reported across studies.

Based on this understanding, the conceptual framework was developed by bringing together the key insights from the literature. The framework provides a structured way to understand how the findings are connected and why different studies report different outcomes.

It is important to note that the framework is conceptual in nature and does not aim to experimentally validate degradation mechanisms. Instead, it helps organize and interpret existing research in a clearer way. The framework therefore serves as a foundation for future studies to further explore and validate these relationships.

3.8 Research Quality

Ensuring research quality is important to maintain the reliability and validity of the findings. In qualitative and literature-based research, the quality of a study is commonly evaluated using the criteria proposed by Lincoln and Guba (1985). Instead of relying on traditional quantitative measures of validity and reliability, they introduced alternative criteria for qualitative research, namely credibility, dependability, transferability, and confirmability. These principles help ensure that the research process is transparent, systematic, and grounded in reliable evidence. In this thesis, these criteria are considered throughout the research design, literature selection, analysis, and findings.

Credibility is ensured by adopting a structured literature review approach to systematically collect and analyse relevant studies related to vibration-induced capacity degradation in LIBs used in electric vehicles. Clear search strategies, defined inclusion and exclusion criteria, and systematic screening of the literature help ensure that the selected studies accurately represent the current state of research. Comparative analysis of experimental parameters such as vibration frequency, acceleration level, and state of charge further supports the reliability of the findings.

Dependability is maintained by documenting the research process in a transparent and traceable manner. The steps involved in the literature search, screening, data extraction, and analysis are clearly described in the methodology chapter. This structured process allows other researchers to understand how the studies were selected and analysed, making the research process consistent and repeatable (Shenton, 2004).

Transferability is supported by clearly describing the context of the selected studies, including the experimental conditions and battery characteristics investigated in the literature. By providing detailed descriptions of vibration parameters, testing conditions, and reported degradation outcomes, the findings of this study may be useful for researchers and practitioners working in similar areas of battery reliability and electric vehicle systems (Lincoln & Guba, 1985).

Confirmability is achieved by grounding the conclusions of the study in evidence reported in the selected literature rather than personal interpretation. The analysis focuses on comparing reported results across studies and identifying patterns and inconsistencies based on documented experimental conditions. By relying on published data and clearly presenting the analysis process, the study reduces the influence of researcher bias and ensures that the conclusions are supported by existing research (Enworo, 2023).

Overall, by following these quality principles, this research provides a transparent and systematic analysis of existing studies on vibration-induced degradation in LIBs, contributing to a clearer understanding of the factors influencing reported experimental outcomes.

3.9 Ethical Considerations

Ethical considerations play an important role in ensuring that research is conducted responsibly and that the findings are reliable and trustworthy. Key ethical principles in academic research include honesty, transparency, and proper acknowledgment of previous work (Resnik, 2018). These principles were followed throughout this study.

This thesis is based on a structured literature review that examines previously published research on vibration-induced capacity degradation in LIBs used in electric vehicles. Since the research relies on secondary data from published studies and does not involve human participants or confidential industrial data, issues such as informed consent or personal data protection are not applicable. Instead, the focus is placed on maintaining transparency in the research process and ensuring that all sources are properly acknowledged.

All studies included in this review were obtained from credible academic sources such as journal articles, conference papers, book chapters, and scholarly books, in accordance with the inclusion criteria defined for the literature search. Proper citation and referencing were maintained to respect the intellectual property of previous researchers and avoid plagiarism.

Following systematic and transparent procedures for literature selection and analysis also helps ensure that the findings are reliable and unbiased (Snyder, 2019).

During the preparation of this thesis, assistive digital tools, including Grammarly, OpenAI ChatGPT, and Anthropic Claude, were used to support content refinement, the development of literature search strings, grammatical improvement, and the assessment of the understanding and relevance of the reviewed literature. These tools were used only as supportive aids during the writing and review process. All ideas, interpretations, conceptual development, and overall academic judgment were independently developed by the authors. After using these tools, the content was carefully reviewed, edited, and validated by the authors, who take full responsibility for the final version of the thesis.

In addition, the study follows general ethical principles for qualitative and literature-based research, including accurate representation of findings and the avoidance of data manipulation or misinterpretation outlined by the Swedish Research Council (2017). The conclusions presented in this thesis are based solely on the selected literature and aim to provide an objective understanding of how vibration conditions affect capacity degradation in lithium-ion batteries.

By following these ethical guidelines, the research maintains academic integrity and ensures that the results presented in this study are credible, transparent, and ethically sound.

4 Result and Analysis

This chapter presents the analysis of vibration-induced capacity degradation in lithium-ion batteries based on the findings of the literature review. The analysis focuses on explaining why previous studies report different degradation outcomes under vibration conditions. By examining the reported evidence, this chapter develops analytical propositions and a conceptual understanding of the factors that shape vibration-related capacity degradation.

4.1 Moderating Factors in Vibration-Induced Capacity Degradation

The literature review in Chapter 2 highlighted significant inconsistencies in the reported effects of vibration on lithium-ion battery capacity degradation. While several studies identify specific vibration frequencies associated with performance deterioration, others report limited or negligible degradation under similar frequency ranges. These contrasting observations suggest that vibration frequency alone may not sufficiently explain the variation in degradation outcomes reported across the literature. A closer examination of existing studies indicates that additional conditions may shape how vibration exposure affects capacity degradation. Differences in mechanical loading severity, electrochemical SOC during testing, evaluation timing, temperature, depth of discharge, and structural configuration of the cells appear to influence the observed degradation behaviour. These factors may alter how vibrational energy is transmitted within the battery and how structural disturbances subsequently influence capacity degradation.

Rather than treating these conditions as independent experimental variables, they can be interpreted as moderating factors that influence the relationship between vibration exposure and capacity degradation. In this context, a moderating factor refers to a variable that changes the strength or nature of the effect that vibration may have on battery capacity degradation (Conway et al., 2007). The presence of such moderating conditions may help explain why studies operating within similar vibration frequency ranges sometimes report substantially different degradation outcomes. To examine this possibility, the following analysis focuses specifically on four moderating factors.

4.2 Structural Configuration

When the findings across vibration-related studies are considered together, it becomes evident that batteries with different physical designs and internal architectures do not always exhibit identical degradation behaviour under comparable vibration conditions. LIBs are manufactured in several formats, including cylindrical, prismatic, and pouch configurations, each characterized by distinct internal structures and mechanical properties. Studies examining these different cell formats often report variations in mechanical sensitivity and degradation behaviour during vibration exposure (Baazouzi et al., 2023; Hooper & Marco, 2015). Cylindrical cells are frequently observed to experience greater structural disturbance under vibration compared with pouch or prismatic cells, while other configurations demonstrate different responses depending on their internal support structures and casing rigidity. These observations indicate that structural design differences between battery cells may influence how mechanical vibration affects battery performance.

This pattern is important because it suggests that vibration-induced capacity degradation cannot be interpreted independently of the physical structure of the battery. In particular, the internal architecture of different battery formats can influence how mechanical stresses develop and propagate within the cell during vibration exposure. In cylindrical cells, the internal structure is compact and mechanically constrained, with wound electrode layers tightly packed within a rigid enclosure. In some designs, a central mandrel may provide additional support that helps maintain the alignment and stability of the internal assembly. Maddipatla et al. (2024); Gelam et al. (2024), describe cylindrical cells as consisting of a tightly wound electrode assembly enclosed within a rigid metal casing, sometimes supported by a central mandrel. Within this configuration, the tightly wound and mechanically constrained internal structure may allow vibration to travel through the cell and create localized mechanical stress in sensitive internal areas. Such areas can include internal contact points and areas around the mandrel or current interrupt device. Studies by Swornowski (2017); Chen et al. (2022); Spielbauer et al. (2021), indicate that vibration can disturb internal battery structures, while the wound cylindrical structure can develop internal stress and displacement that can lead to local contact-related damage under mechanical loading.

In contrast, pouch cells have a comparatively less rigid internal architecture, as their stacked electrode layers are enclosed within a flexible laminated casing rather than a rigid metallic enclosure. These structural arrangements may allow mechanical loads to be distributed more evenly across the layered assembly, which could alter the transmission and localization of vibration-induced stresses within the cell. This structural arrangement is consistent with descriptions of pouch-cell configurations in the literature, where cells are characterized by stacked electrode layers enclosed within a flexible laminated structure (Günter & Wassiliadis, 2022; Ladpli et al., 2019; Berg et al., 2019). Similarly, differences in internal clearances, electrode stacking arrangements, and casing stiffness may influence how vibration-induced forces are transferred through the battery structure. This indicates that the internal design of the cell can affect its mechanical response under vibration. This relationship is evident in the studies of Akbari and Voyiadjis (2024); Kisters et al. (2021); Spielbauer et al. (2022), where variations in structural design are associated with how mechanical loads are distributed within the battery.

Overall, the evidence from the reviewed studies suggests that battery structural configuration conditions how vibration loading relates to capacity degradation. Differences in cell format, internal architecture, and mechanical support structures can alter the mechanical response of the battery during vibration exposure, which may determine the extent to which structural disturbances develop within the cell. As a result, differences in battery design across experimental studies may contribute to the variation in degradation behaviour reported in the vibration literature.

Proposition 1. *Structural configuration conditions how vibration loading translates into capacity degradation in lithium-ion batteries.*

4.3 Evaluation Timing

Across the reviewed vibration studies, differences in the reported severity of capacity degradation appear to be associated not only with the applied vibration conditions but also with the point at which battery performance is evaluated after vibration exposure. When the findings from these studies are examined collectively, two distinct evaluation approaches can be observed. Some studies assess battery performance immediately after vibration exposure by measuring parameters such as discharge capacity or internal resistance directly following the vibration event. Under these conditions, only small or moderate changes in performance are typically reported. In contrast, other studies evaluate battery behaviour after the vibrated cells have undergone additional charge-discharge cycling. In these cases, cells previously exposed to vibration often exhibit greater capacity degradation compared with non-vibrated reference cells during subsequent operation.

This pattern indicates that vibration-induced degradation may not always be immediately detectable through conventional post-test measurements. If the degradation process occurred entirely during the vibration event, similar results would be expected regardless of whether performance is evaluated immediately or after further battery operation. Instead, several studies report that degradation becomes more evident during later charge-discharge cycling, suggesting that the effects of vibration exposure may develop progressively rather than appearing instantaneously. Differences in evaluation timing may therefore influence how the severity of vibration-induced capacity degradation is observed and interpreted across experimental studies.

These internal disturbances may arise when vibration affects the mechanical condition of the battery without immediately producing a clear electrochemical response. In such cases, small changes within the internal structure can remain difficult to detect at first, even though they may still influence the integrity of the cell. Swornowski (2017) and Soudbakhsh et al. (2020) suggest that vibration or mechanical damage can disturb internal battery structures even when the battery shows little immediate change in measurable electrochemical behaviour. Mechanical excitation may introduce small internal changes within the battery, including slight shifts in component position, changes at contact points, or localized stress build-up within the electrode stack and current collector regions. Although these disturbances affect the internal mechanical condition of the cell, they may not immediately produce a measurable loss in electrochemical performance. Further highlighted by Song et al. (2023); Lu et al. (2015); Yin et al. (2020) that mechanical loading can contribute to localized stress build-up, interface degradation, and contact-related damage within the battery structure.

As battery operation continues, these internal changes may begin to affect electrochemical behaviour more noticeably. Repeated charge-discharge cycling can gradually intensify the effects of earlier structural disturbances, leading to progressive degradation mechanisms such as increased internal resistance, loss of electrical contact, and gradual deterioration of electrode interfaces. Pouraghajan et al. (2021), Müller et al. (2018), and Lu et al. (2015) note that continued cycling can promote resistance growth, contact loss, and interface degradation within the battery structure. Consequently, the effects of vibration exposure may become more evident during later stages of battery operation rather than being fully observable immediately after the vibration event. Goodman et al. (2020) further indicate that internal damage can remain

difficult to detect at an early stage, even though it may later influence the behaviour and integrity of the cell.

The observations from the reviewed studies, therefore, suggest that evaluation timing affects how vibration-induced capacity degradation is identified and interpreted. Differences in the timing of post-vibration performance assessment can contribute to variations in the degradation outcomes reported across the vibration literature.

Proposition 2. *Vibration-related degradation effects become more evident when capacity degradation is evaluated after subsequent charge–discharge cycling.*

4.4 Electrochemical State of Charge

When results from different studies are examined together, a pattern becomes apparent. Experiments that evaluate cells under multiple SOC conditions often report greater capacity degradation and resistance growth when batteries are exposed to vibration at higher charge states under similar vibration loading conditions. Several vibration studies, however, conduct testing at a fixed intermediate SOC level, commonly around 50%. This observation indicates that the electrochemical state of the battery can affect the sensitivity of the cell to mechanical disturbances. Changes occurring within electrode materials during charging and discharging provide a possible explanation for this behaviour. At higher SOC levels, a greater amount of lithium becomes inserted within the electrode structure, which can lead to structural expansion and changes in the internal stress distribution of the electrode materials. These changes may alter the mechanical behaviour of the electrode layers and influence the stability of internal interfaces within the cell. As a result, the response of the battery to external mechanical loading such, as vibration may vary depending on the state of charge. This behaviour is further supported by Li et al. (2018); Li and Wang (2020), who report that increased lithiation can affect the mechanical properties of electrode materials and the stability of internal interfaces.

Changes in the electrochemical condition of the battery can influence the stiffness and dynamic response of the cell. This may affect how externally applied vibration loads are transferred through the battery structure and how mechanical stresses interact with internal components during vibration exposure. As a result, vibration-induced stresses may interact more strongly with the electrochemically stressed structure of the battery, increasing the potential of internal structural disturbances that later contribute to capacity degradation. Shi et al. (2016); Xu et al. (2016) similarly describe how the electrochemical condition of lithium-ion batteries can affect their mechanical behaviour, structural integrity, and response to external mechanical loading.

At lower or moderate SOC levels, the internal mechanical state of the battery remains comparatively less critical, which can limit the extent to which vibration-induced stresses disrupt the internal structure of the cell. Under these conditions, the battery may be less prone to severe structural or electrochemical damage during vibration exposure. This pattern is consistent with the findings of An et al. (2024); Shi et al. (2024), who indicate that lower SOC conditions are associated with a less severe mechanical response and reduced damage development under external loading.

The observations discussed above indicate that the electrochemical state of charge is not merely an operational parameter, but also a factor that influences how mechanical stresses interact with

the internal structure of the cell during vibration exposure. Consequently, differences in SOC across experimental studies may contribute to variations in the severity of degradation reported in the vibration literature.

Proposition 3: *The degradation response of lithium-ion batteries to vibration exposure varies depending on the state of charge of the cell.*

4.5 Mechanical Loading Severity

The evidence from the vibration literature indicates that the severity of mechanical loading is closely associated with the extent to which vibration exposure leads to capacity degradation in lithium-ion batteries. A consistent pattern can be observed across the reviewed studies. Experiments that apply intensified vibration conditions or repeated mechanical shocks tend to report greater electrochemical degradation, including faster capacity fade and increased internal resistance. Studies conducted under standardized automotive test conditions or shorter vibration exposure durations, in contrast, often report only moderate performance changes or minimal degradation effects. This pattern suggests that the amount of mechanical energy transmitted into the cell may affect whether vibration exposure results in measurable electrochemical degradation.

This observation is particularly notable because many of the reviewed studies operate within broadly similar vibration frequency ranges. If vibration frequency alone determined degradation behaviour, similar outcomes would be expected across these experiments. However, the literature shows considerable variation in degradation severity depending on the intensity of the mechanical loading applied. This suggests that the relationship between vibration exposure and capacity degradation cannot be explained solely by vibration frequency. Instead, the magnitude of the mechanical loading appears to shape how vibrational stresses are transmitted and accumulated within the battery structure.

One explanation for this behaviour relates to the accumulation of mechanical stresses within the internal structure of Li-ion cells when they are exposed to intensified vibration conditions. Higher acceleration levels and repeated shock loading can increase the mechanical forces transmitted through the electrode stack, current collectors, and other internal connections of the cell. Previous studies have reported that mechanical stresses within LIBs can lead to structural changes in electrode materials, including particle fracture, electrode cracking, and loss of electrical contact between components (Edge et al., 2021; Müller et al., 2018). These forms of structural degradation can disrupt internal electrical pathways and affect the stability of the electrode structure during operation.

From this perspective, intensified mechanical loading during vibration exposure may increase the likelihood that such stress-related degradation processes develop within the cell. Studies examining the mechanical behaviour of electrode materials have similarly shown that repeated mechanical loading can promote deformation of electrode structures and the formation of internal cracks over time (Pistorio et al., 2023; Wu et al., 2024). Such structural changes can reduce the effective connectivity of active materials and contribute to increased internal resistance and capacity loss during continued cycling (Yan et al., 2017; Cortada et al., 2020).

Under milder mechanical loading conditions, however, the stresses transmitted to the internal battery structure may remain relatively limited, which can reduce the likelihood that significant structural damage develops within the cell. Structural degradation mechanisms such as particle fracture and crack formation tend to become more pronounced when mechanical stresses accumulate beyond certain levels, as discussed in studies of lithium-ion battery materials (Li et al., 2024; Rahman et al., 2024; Ebner et al., 2013). When mechanical loading remains comparatively low, these damage processes may develop more gradually or remain limited, resulting in smaller or less noticeable changes in electrochemical performance. Overall, batteries exposed to higher acceleration levels or repeated mechanical shocks tend to exhibit more pronounced degradation effects. Under milder loading conditions, the stresses transmitted to internal battery components may remain limited, resulting in slower or less noticeable degradation.

Proposition 4. *The severity of mechanical loading during vibration exposure increases the likelihood of capacity degradation in lithium-ion batteries.*

4.6 Conceptual Framework of Vibration-Induced Capacity Degradation

Based on the propositions developed in Sections 4.2 to 4.5, vibration-induced capacity degradation in LIBs does not appear to depend solely on vibration exposure. Instead, the impact of vibration may vary depending on several moderating factors. The analysis suggests that structural configuration, evaluation timing, Electrochemical SOC, and mechanical loading severity can influence how vibration affects battery performance. These factors, therefore, act as moderating conditions that shape the relationship between vibration loading and observed capacity degradation.

To illustrate this relationship, a conceptual framework is proposed in figure 4. The framework shows vibration exposure as the primary influencing factor, while the identified moderating factors influence how vibration effects translate into capacity degradation. This model provides a simplified representation of the relationships identified in the analysis.

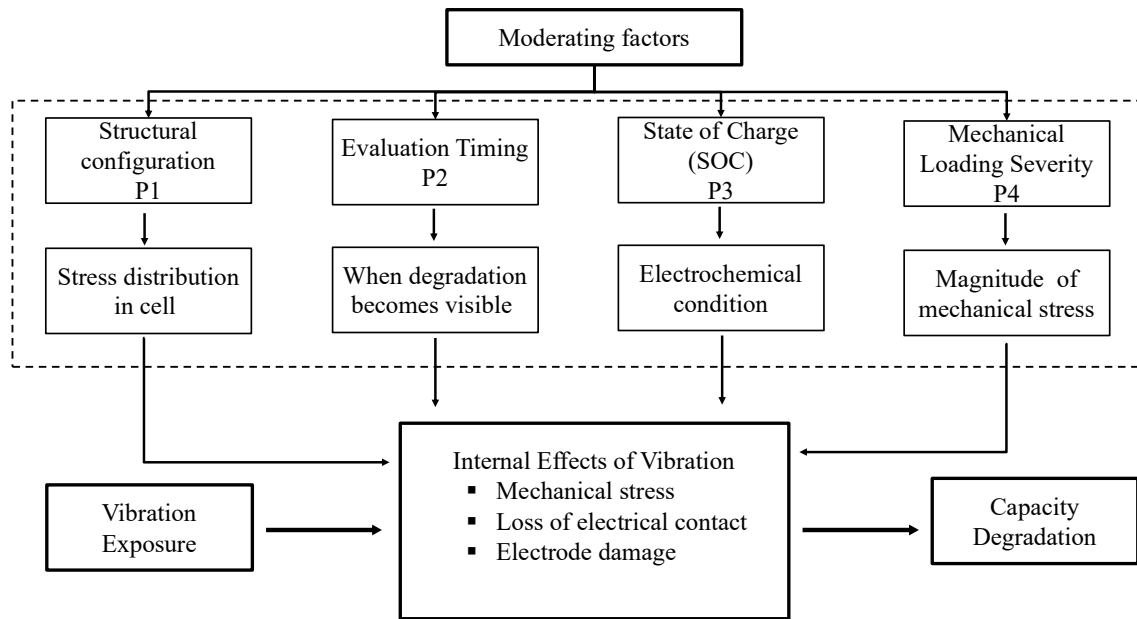


Figure 4. Conceptual framework for explaining inconsistencies in the literature

5 Discussion

This chapter discusses and interprets the findings obtained from the literature analysis presented in the previous chapter. While Chapter 4 focused on identifying patterns and observations from the selected studies, this chapter interprets these findings in relation to the research questions and provides a clearer understanding of vibration-induced capacity degradation in lithium-ion batteries used in electric vehicles.

5.1 Overview of Findings

The comparative analysis of the literature indicates that mechanical vibration has the potential to influence the performance and degradation behaviour of LIBs. However, the reported results across studies vary, and different studies have reported different degradation outcomes under vibration exposure. These variations suggest that the relationship between vibration conditions and battery degradation is complex and influenced by multiple aspects of the experimental context.

To better understand these findings, this chapter examines the results in relation to the research questions of the study. First, the current understanding of vibration-related battery degradation reported in the literature is discussed. Next, the inconsistencies identified across previous studies are examined to understand why different degradation outcomes have been reported. Finally, the conceptual framework proposed in this research is discussed to explain how variations in research conditions may influence the degradation behaviour observed in vibration studies.

5.2 Addressing the Research Questions

5.2.1 RQ1. What is the current state of research on the capacity degradation of lithium-ion batteries in electric vehicles due to mechanical vibration frequency?

The first research question focused on understanding how previous studies collect data on capacity degradation in LIBs when they are exposed to vibration. Based on the literature reviewed in this thesis, most of this data comes from laboratory-based experimental studies that examine the vibration conditions that batteries may experience in electric vehicles.

In these experiments, researchers usually expose battery cells to controlled vibration using testing equipment designed to simulate real operating conditions. The vibration is applied under specific test conditions, such as selected frequency ranges, acceleration levels, and exposure times. In many cases, these conditions are based on standardized testing procedures or on experimental setups developed to represent vehicle-related vibration environments.

To determine whether vibration affects battery performance, the battery is usually tested before and after vibration exposure. The most common way of doing this is by measuring discharge capacity, since this gives a direct indication of how much energy the battery can still store and deliver. If the measured capacity decreases after the vibration test, this is taken as evidence that some form of degradation may have occurred.

Besides capacity measurements, some studies also look at other indicators to better understand what is happening inside the battery. These include changes in internal resistance, impedance behaviour, and in some cases physical or structural changes inside the cell. By combining these types of measurements, researchers can get a clearer picture of how vibration may influence both the mechanical and electrochemical behaviour of the battery.

Overall, the literature shows that data on vibration-induced capacity degradation is obtained through both theoretical explanations and experimental testing. These studies provide useful insights, but they also use different test conditions and evaluation methods. Because of this, the reported results are not always easy to compare directly. This becomes important in the next research question, where the inconsistencies across studies are discussed.

5.2.2 RQ2. What inconsistencies exist between studies regarding critical vibration frequencies and capacity degradation magnitude in lithium-ion batteries?

The second research question aimed to examine the inconsistencies reported in the literature regarding vibration-induced capacity degradation in lithium-ion batteries. Although many studies investigate the effect of vibration on battery degradation, the results reported across the literature are not always consistent. The analysis presented in the previous chapter revealed that different studies report varying levels of degradation and, in some cases, identify different vibration conditions as being critical for degradation.

One of the main inconsistencies observed in the literature relates to the magnitude of capacity degradation reported under vibration exposure. While some studies report noticeable reductions in battery capacity after vibration testing, other studies observe only minor or negligible changes in electrochemical performance. These variations make it difficult to draw a clear conclusion about the overall impact of vibration on LIB capacity degradation.

Another inconsistency concerns the vibration conditions under which degradation effects are observed. In several studies, certain frequency ranges are suggested to have a stronger influence on battery performance, whereas other studies report different frequency responses or do not identify a clear critical frequency. These differences suggest that the relationship between vibration conditions and capacity degradation is not straightforward and may depend on additional aspects of the experimental setup.

The analysis also indicates that variations in testing procedures and evaluation methods across studies contribute to the inconsistencies reported in the literature. Different experimental setups, testing durations, and performance evaluation methods can influence how degradation behaviour is observed and reported. As a result, similar vibration conditions may lead to different reported outcomes depending on how the experiments are designed and how the battery capacity level is evaluated.

Rather than representing contradictory findings, these inconsistencies highlight the complexity of vibration-induced capacity degradation behaviour in lithium-ion batteries. The variations observed across studies suggest that the degradation process is influenced by multiple interacting conditions rather than a single parameter such as vibration frequency alone. Recognizing these differences is therefore important for interpreting the results reported in the literature.

The presence of these inconsistencies indicates the need for a structured way to interpret the variations observed across studies. This leads to the third research question, which aims to develop a conceptual framework that helps explain how differences in research conditions may influence the degradation outcomes reported in the literature.

5.2.3 RQ3. What moderating factors can explain why existing studies report inconsistent findings on the relationship between vibration frequency and capacity degradation in lithium-ion batteries?

The findings of this study indicate that the inconsistencies reported in the literature cannot be explained by vibration frequency alone. Although several studies investigate the influence of vibration frequency on battery degradation, the reported results differ considerably in terms of critical frequency ranges, degradation magnitude, and the occurrence of measurable capacity loss. These differences suggest that additional conditions influence how vibration exposure affects battery performance.

Based on the comparative analysis of the literature, four moderating factors were identified that help explain these variations: structural configuration, evaluation timing, electrochemical state of charge, and mechanical loading severity. Structural configuration influences how mechanical stresses are distributed within the battery, meaning that cells with different internal designs may respond differently to similar vibration conditions. Evaluation timing affects whether degradation becomes visible immediately after vibration exposure or only during subsequent cycling. The electrochemical state of charge alters the internal mechanical and electrochemical condition of the cell, which can influence its sensitivity to vibration. Mechanical loading severity determines the intensity of the mechanical stresses applied to the battery during vibration testing.

The inconsistent findings reported across the literature can therefore be understood as the result of differences in experimental conditions and battery characteristics rather than the effect of vibration frequency alone.

6 Conclusion

6.1 Summary of Findings

The increasing adoption of electric vehicles has brought greater attention to the reliability and long-term performance of lithium-ion batteries. During vehicle operation, battery systems are continuously exposed to mechanical vibrations generated by road conditions, vehicle movement, and structural interactions. These vibrations may influence the internal structure and electrochemical behaviour of battery cells, potentially contributing to capacity degradation over time. Although several studies have investigated the effect of vibration on LIBs, the findings reported in the literature are often inconsistent, making it difficult to clearly understand the extent to which vibration influences battery degradation.

The aim of this thesis was to examine how vibration affects capacity degradation in LIBs used in electric vehicle applications and to understand why different studies report varying degradation outcomes. In particular, the research aimed to review the existing literature on vibration-induced capacity degradation, identify inconsistencies in reported findings, and develop a conceptual explanation to help interpret these variations.

To achieve this objective, the study adopted a structured literature review approach. Relevant studies were systematically identified through defined search strategies and screening procedures to ensure that the selected literature was closely related to the research topic. The selected studies were then analysed to examine how vibration exposure has been studied in previous research and how capacity degradation has been reported under different experimental conditions.

The analysis revealed that although vibration can influence the performance of LIBs, the extent of degradation reported across studies varies considerably. While some studies observe noticeable capacity degradation after vibration exposure, others report relatively minor or negligible effects. These differences indicate that the relationship between vibration conditions and battery degradation is complex and influenced by variations in experimental setups, testing procedures, and battery characteristics.

Based on the insights obtained from the literature review and analysis, this study developed a conceptual framework to provide a structured interpretation of the inconsistencies observed in previous research. The framework provides a clearer way of interpreting why studies report different capacity degradation outcomes under vibration exposure and highlights the importance of considering these patterns. The study identifies moderating factors that help explain why different studies report different results. In this way, the framework shows how variations in research conditions may influence the capacity degradation outcomes reported in vibration studies. By synthesizing findings from existing literature, this thesis contributes to a clearer understanding of vibration-induced capacity degradation in LIBs and provides a basis for future research in this area.

6.2 Future Work

This study identified several moderating factors that may influence the extent to which vibration exposure contributes to capacity degradation in LIBs. Since the current research is based on a comparative analysis of existing literature, future work should focus on experimentally validating these factors under controlled vibration conditions. Studies could systematically vary mechanical loading severity, state of charge, structural configuration, and evaluation timing to examine how each factor affects vibration-induced capacity degradation. Future research should also investigate how these factors interact, since capacity degradation is likely influenced by the combined effects of mechanical and electrochemical conditions rather than by a single variable alone. In addition, long-term post-vibration cycling experiments would help determine whether vibration introduces latent structural damage that becomes more apparent as capacity degrades over continued battery operation. Finally, computational modelling and simulation could be used to further explore these interactions and support the design of future experimental studies.

6.3 Final Remarks

This study offers a conceptual guide for understanding why different studies report inconsistent results on vibration-induced capacity degradation in LIBs. By identifying the moderating factors that affect these differences, this thesis reframes existing inconsistencies as explainable variations rather than contradictions.

However, this study encountered certain limitations during the research process. Finding studies that specifically investigated the relationship between vibration frequency and capacity degradation proved to be challenging. The available literature on this topic is limited, as most existing vibration studies on LIBs focus primarily on thermal effects, structural integrity, or impedance changes rather than on capacity degradation as the primary outcome. A considerable number of the studies eventually included were identified through snowballing rather than through direct search results, reflecting the scattered and emerging nature of this research area. Since only a limited number of studies directly focused on this topic, the analysis sometimes relied on studies that covered related but not identical aspects, which may have made the conclusions less specific than they could have been with more directly relevant research. Furthermore, the time available for this study was limited, so not every aspect of the topic could be explored in depth. Despite these limitations, the conceptual framework and moderating factors proposed in this thesis offer a useful starting point for future experimental studies.

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