UNPAD
Vol. 10, No. 01 (2026) 28 – 43
JIIF (Jurnal Ilmu dan Inovasi Fisika)
https://jurnal.unpad.ac.id/jiif/
SINTA 3

NICKEL/COBALT/MANGANESE INFLUENCE TO COULOMBIC/RETENTION/CAPACITY EFFICIENCY IN LIGHT ELECTRIC VEHICLE (LEV) BATTERY LIFECYCLE: SISTEMATIC LITERATURE REVIEW

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Submitted: 26/11/2025
Accepted: 12/01/2026
Published: 12/02/2026

Abstract. The global energy transition driven by the challenges of climate change and the mitigation of greenhouse gas emissions has positioned Light Electric Vehicles (LEVs) as a strategic mobility solution in urban environments. The reliability and sustainability of LEVs are highly dependent on the optimization of lithium-ion batteries, particularly the composition of Nickel/Cobalt/Manganese (NCM) cathode materials. This Systematic literature review (SLR) aims to critically analyze the influence of the ratio of Ni, Co and Mn elements on three electrochemical performance metrics, namely specific capacity, coulombic efficiency (EC) and capacity retention. Applying the PRISMA methodology, 12 relevant studies were selected for analysis. The results of the review show that there is a significant performance trade-off in the NCM cathode. The high Nickel (Ni) content serves to increase the specific capacity up to 220 mAh g^{-1}. However, the proportion of Ni-rich 0.90 to 0.95 increases the material's susceptibility thereby triggering extreme performance fluctuations and decreased retention caused by cation mixing and the volumetric instability of the lattice. In contrast, Manganese (Mn) and Cobalt (Co) act as structural stabilizers. Manganese (Mn) shows a U-shape performance pattern at coulombic efficiency (EC) and retention with a concentration of 0.35 achieving optimal performance of 93% coulombic efficiency. Meanwhile, a low Cobalt (Co) concentration of 0.05 provides an optimal balance between coulombic efficiency of 93% and capacity retention of 95% although a peak retention point of 98% is achieved at Co 0.15.

Keywords: Battery, Cycle life, Retention Capacity, Ligh Electric Vehicles, NCM

Abstrak. *Transisi energi global yang didorong oleh tantangan perubahan iklim dan mitigasi emisi gas rumah kaca telah memosisikan Light Electric Vehicles (LEV) sebagai solusi mobilitas strategi di lingkungan perkotaan. Keandalan dan keberlanjutan LEV sangat bergantung pada optimalisasi baterai lithium-ion, khususnya komposisi material katoda Nikel/Kobalt/Mangan (NCM). Systematic literature review (SLR) ini bertujuan untuk menganalisis secara kritis pengaruh rasio unsur Ni, Co dan Mn terhadap tiga metrik performa elektrokimia yaitu kapasitas spesifik, efisiensi coulombic (EC) dan retensi kapasitas. Menerapkan metodologi PRISMA, terpilih 12 studi relevan untuk analisis. Hasil tinjauan menunjukkan adanya trade-off performa*

DOI: https://doi.org/10.24198/jiif.v10i1.68348 e-ISSN: 2549-7014

yang signifikan pada katoda NCM. Kandungan Nikel (Ni) yang tinggi berfungsi meningkatkan kapasitas spesifik hingga 220 mAh g-1. Namun, proporsi Ni-rich 0,90 hingga 0,95 meningkatkan kerentanan material sehingga memicu fluktuasi kinerja yang ektrem dan penurunan retensi yang disebabkan oleh percampuran kation dan ketidakstabilan volumetrik kisi. Sebaliknya, Mangan (Mn) dan Kobalt (Co) berperan sebagai stabilitator struktural. Mangan (Mn) menunjukkan pola kinerja U-shape pada efisiensi coulombic (EC) dan retensi dengan konsentrasi 0,35 mencapai kinerja optimal efisiensi coulombic 93%. Sementara itu, konsentrasi Kobalt (Co) rendah sebesar 0,05 memberikan keseimbangan optimal antara efisiensi coulombic 93% dan retensi kapasitas 95% meskipun titik retensi puncak 98% tercapai pada Co 0.15.

Kata kunci: *Battery, Cycle life, Kapasitas Retensi, Ligh Electric Vehicles, NCM*

1. Introduction

Global challenges in recent decades such as climate change, increased greenhouse gas emissions and changes in air quality in urban areas have driven the transition to cleaner and more sustainable systems. The transportation sector is a significant contributor to global carbon emissions, which is a major focus in decarbonization efforts. Transportation electrification is seen as a strategic solution to reduce dependence on fossil fuels while reducing emissions and improving air quality [1], [2].

Light Electric Vehicles (LEVs) such as electric motorcycles, scooters and electric bicycles play an important role in the context of transportation electrification. LEV offers efficient mobility solutions especially in urban areas with high congestion levels and short-distance travel needs. The LEV market in developing countries, especially in Asia, is showing very rapid growth as the need for affordable and environmentally friendly transportation increases. In contrast to battery-based electric vehicles (BEV) which are large in size. LEV has the characteristics of lighter and more flexible energy needs. The successful implementation of LEV widely depends heavily on advances in energy storage technology especially in terms of efficiency, durability and battery cost [3], [4], [5].

Lithium-ion batteries are currently the main technology used in LEV vehicles. This is due to its superior characteristics, namely high energy density, light weight and long life cycle. The performance of Li-ion batteries is greatly influenced by the composition of the material in them, especially the cathode material which plays an important role in determining the efficiency and durability of the battery. The type of cathode material that is widely used in Li-ion batteries is NCM, which is a mixture of the elements Nickel (Ni), Cobalt (Co) and Manganese (Mn). Each element has a specific function, namely Nickel contributes to high specific capacity, Cobalt provides structural stability and supports fast charging and discharging performance, while Manganese improves thermal stability and helps to reduce production costs. Variations in composition ratios such as NCM111, NCM523 and NCM811 show differences in performance characteristics that allow for adjustments as needed [6]-[9].

The life cycle is one of the challenges in the development of batteries for LEV vehicles, especially in long-term reliability. Generally, LEV batteries undergo intensive charging and discharging cycles during their operational life. Cycle life indicates whether the battery is working or not but also refers to a gradual decline in performance, such as a decrease in energy storage capacity as the number of cycles increases [10]-[13]. The assessment of battery performance is carried out through the three parameters shown in this review literature. Specific capacity indicates the amount of energy stored by the battery in each unit of mass and reflects the efficiency of the active material. Coulombic efficiency (EC) measures the ratio between capacity at discharge and capacity at fill. Discharge and charge are measured with high coulombic efficiency values indicating minimal energy loss in each cycle. Capacity retention describes the ability of a battery to maintain capacity after a cycle and is a direct indicator of the lifecycle durability of the battery [14]-[17].

Although the literature on NCM cathode materials in Li-ion batteries is abundant, the majority of research is still biased on High Performance Battery Electric Vehicle (BEV) applications and ignores the operational cycle characteristics of Light Electric Vehicles (LEVs). In addition, thermal stability evaluations are still often carried out separately, without examining in depth their relationship with electrochemical performance parameters such as capacity, coulombic efficiency and capacity retention. This condition indicates that the interaction between material composition and LEV requirements, especially the trade-off between energy density and cycle resilience, has not been fully integrated. Responding to this gap, this SLR offers a novelty by evaluating the influence of the composition of Nickel, Cobalt and Manganese specifically for LEV needs. This study consolidates the relationships between parameters to map the optimal NCM ratio.

2. Research Methods

This review was conducted using the Preferred Reporting Items for Systematic review and Meta-Analyses (PRISMA) method with several stages, namely Identification, Screening, and included. At the identification stage, the keywords "NCM cathode material", "(Co or Mn)", "Lithium-ion", "capacity retention" with the connecting word "AND" were selected. The article search was conducted using several databases, namely Sciencedirect, Springer Nature and Taylor and Franch. Results from Sciencedirect resulted in 4,053 articles, Taylor and Franch produced 24 articles and Springer Nature produced 750. The overall total of the three databases was obtained at 4,827 articles.

Furthermore, the entire article in Screening consists of records screened, Reports sought for retrieval and Reports assessed for eligibility. The results of records sceeneds by year 2020 – 2025 obtained 4,067 articles, Records excluded between three database articles with records screeneds obtained 760 articles. In Reports sought for retrieval based on the type of article, namely research articles, 2,882 articles were obtained, Reports not retrieved between the year and the article type were 1,182 articles. Furthermore, Reports assessed for eligibility based on open access obtained 298 articles. In excluded Reports, namely duplicates, titles and absabs. Duplicate scoping was obtained 22 articles, titles and abstracts were obtained 264 articles.

The document screening process which ended with the included stage resulted in as many as 12 selected articles to be analyzed. The review process using the PRISMA method is shown in Figure 1. The article was then analyzed based on the composition of NCM, Coulombic Efficiency (%), Capacity (mAh g^{-1}), Capacity retention at 100 cycles (%) and voltage (V), Retention at additional cycles (%) and voltage (V). The extraction process was carried out manually by collecting information from tables and graphs in the primary study. To ensure comparability between studies, all capacity units were standardized to mAh g-1 and capacity retention data were standardized at an equivalent number of 100 cycles.

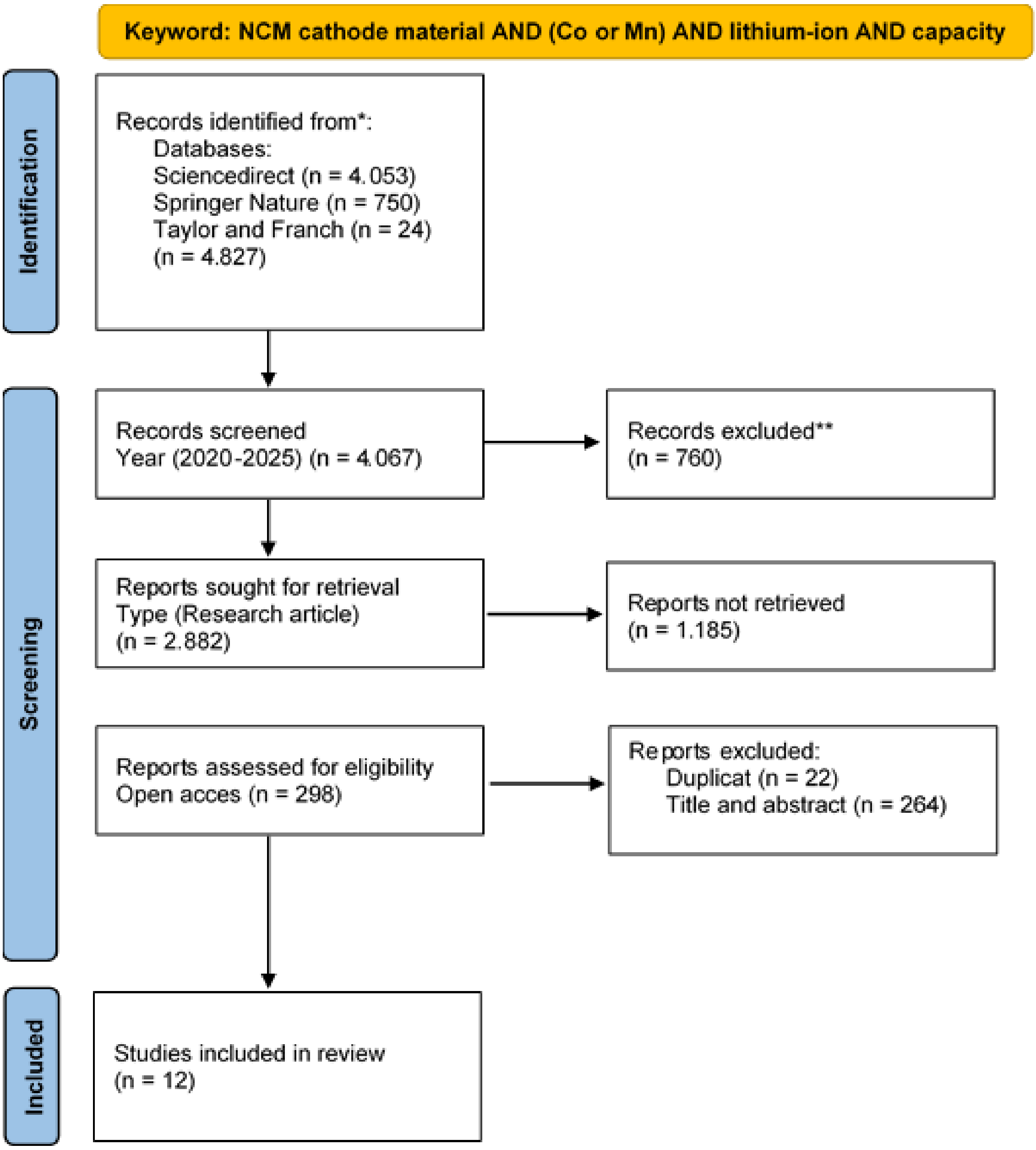

Figure 1. PRISMA Literature Review

3. Result and Discussion

3.1 Nickel/Cobalt/Manganese Review Data

This review collected secondary data from a wide range of literature to evaluate the electrochemical performance of NCM cathode materials. Table 1 summarizes the main parameters that include coulombic efficiency, capacity and retention. The other four articles were not included in the comparison table because they did not present data on the three variables simultaneously and used NCM variants that were not the same, so it was feared that it would cause bias in the comparative analysis.

Table 1. NCM Cathode Material Data

Nikel/Cobalt/Manganese	Coulombic efficiency (%)	Capacity (mAh g^{-1})	Capacity retention (%) on 100 cycles	Ref
$LiNi_{0.8}Co_{0.15}Mn_{0.05}O_2$	87.9	180.8	97.3	[18]
$LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$	87.2	159.3	76.4	[19]
$LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$	85.33	140.04	75.16	[20]
$LiNi_{0.6}Co_{0.05}Mn_{0.35}O_2$	93.4	158.2	95.8	[21]
$LiNi_{0.9}Co_{0.05}Mn_{0.05}O_2$	83.4	157.4	77.1	[22]
$LiNi_{0.92}Co_{0.05}Mn_{0.03}O_2$	87.0	156.21	79.3	[23]
$LiNi_{0.95}Co_{0.025}Mn_{0.025}O_2$	97	221.5	85.1	[24]
$LiNi_{0.91}Co_{0.06}Mn_{0.03}O_2$	-	213.5	68.1	[25]

Next, data extraction was performed to identify specific correlations between the concentration of transition metals and performance parameters. The initial part of the analysis focuses attention on the role of Manganese (Mn) in influencing coulombic efficiency. Table 2 presents the details of the data as follows:

Table 2. Effect of Manganese on Coulombic Efficiency (%)

Manganese (Mn)	Coulombic efficiency (%)
0.05	87.9
0.2	87.2
0.3	85.33
0.35	93.4

Manganese variations affect the structural integrity of the material significantly during the cycling process. Table 3 presents data on the effect of manganese addition on capacity retention after passing 100 cycles:

Table 3. Effect of Manganese on Retention (%)

Manganese (Mn)	Retention (%)
0.05	97.3
0.2	76.4
0.3	75.16
0.35	95.8

Nickel (Ni) is the main determinant factor in determining the energy density of the battery. **Table 4** summarizes the effect of nickel concentration on capacity.

Table 4. Effect of Nickel on Capacity (mAh g^{-1})

Nickel (Ni)	Capacity (mAh g^{-1})
0.05	157.4
0.2	213.5
0.3	156.21
0.35	221.5

High nickel content lowers thermal stability and material cycle resistance. **Table 5** presents an analysis of the relationship between nickel concentration and retention.

Table 5. Effect of Nickel on Retention (%)

Nickel (Ni)	Retention (%)
0.05	77.1

0.2	68.1
0.3	79.3
0.35	85.1

Cobalt facilitates the diffusion kinetics of lithium ions and improves the efficiency of charge reversibility. **Table 6** shows the effect of cobalt variation on coulombic efficiency.

Table 6. Effect of Cobalt on Coulombic Efficiency (%)

Cobalt (Co)	Coulombic efficiency (%)
0.05	93.4
0.1	85.33
0.15	87.9
0.2	87.2

Cobalt plays a role in suppressing the cation mixing phenomenon to maintain long-term cycle stability. **Table 7** contains the relationship between cobalt and retention.

Table 7. Effect of Cobalt on Retention (%)

Cobalt (Co)	Retention (%)
0.05	95.8
0.1	75.16
0.15	97.3
0.2	76.4

3.2 Effect of Manganese (Mn) on Coulombic Efficiency and Retention

Manganese (Mn) is one of the components that determines the structural stability of battery cathode materials. The following analysis outlines the impact of Mn concentration variations on coulombic efficiency (EC), illustrated in Figure 2.

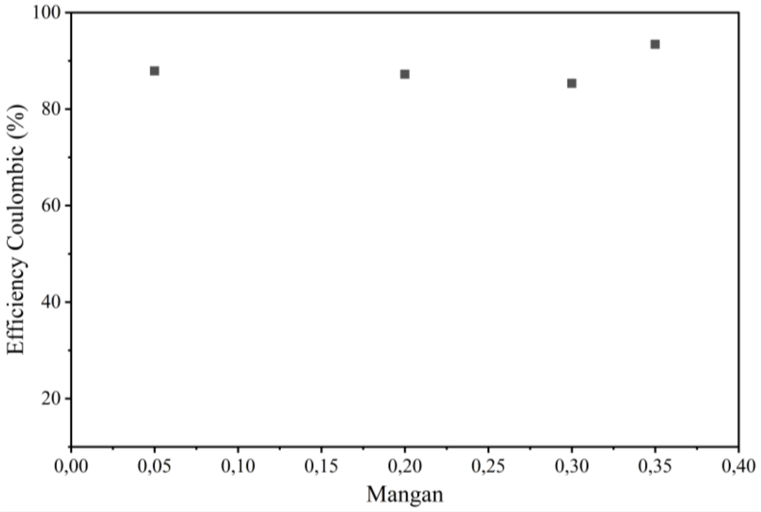

Figure 2. Effect of Manganese on Coulombic Efficiency (%).

Data analysis shows that Coulombic Efficiency (EC) is consistently at a high level, never dropping below 80% of all measurement points. There was a fluctuation in the efficiency value starting from 87.9% at Mn 0.05, then decreasing slightly to 87.2% at Mn 0.2 and reaching the lowest point at Mn 0.3 which was 85%. However, there was a significant increase in the latest data, where at Mn 0.35 EC reached its peak value of 93%. This indicates that despite a slight decrease in intermediate concentrations, Mn levels show the most optimal performance improvement in coulombic efficiency (EC).

Mn serves to improve structural and thermal stability as illustrated in figure 2. A significant increase in EC at a concentration of Mn 0.35 indicates that Mn manages to form a much sturdier and more stable material structure. This stable structure effectively suppresses material degradation and drastic volume changes during the filling and discharging cycles [26]. In addition, the thermal stability better reduces the occurrence of unwanted reactions between the electrode and the electrolyte. This reaction is the main cause of the loss of charge (lithium ions). With minimal side reactions and structural damage, fewer lithium ions are permanently lost causing the coulombic efficiency to increase drastically [27].

On the other hand, the slight decrease in efficiency that occurred between Mn 0.05 and Mn 0.3 indicates the possibility that at intermediate concentrations, the addition of Mn has not reached the optimal level to provide full stability. As a result, Mn actually exerts a slight stress on the crystal structure or changes the ionic conductivity slightly, triggering a minor discharge loss mechanism [28]. This indicates a trade-off where the full stability effect of Mn will be completely dominant and outweigh minor losses when the concentration reaches a higher level of Mn [29], [30].

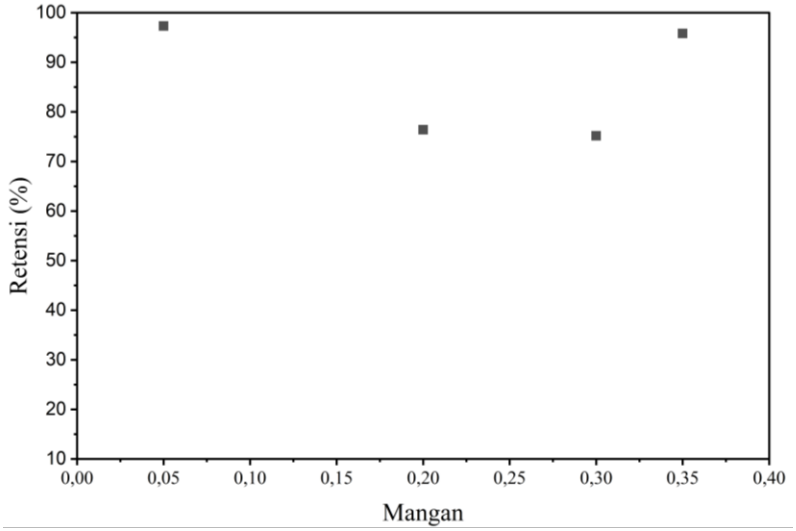

Figure 3 Effect of Manganese on Retention (%).

Retention started from a very high value of 97% at Mn 0.05, then decreased at Mn 0.2 by 76%. The decline in retention continued until it reached a low point of Mn 0.3 which was 75%. Furthermore, the addition of Mn of 0.35 has an effect on retention, which jumps close to the starting point of 95%. The decrease and increase in retention suggest that the influence of Mn on the stability of the structure is highly dependent on its concentration. The decrease in retention at Mn 0.2 and 0.3 indicates that the intermediate concentration level, Mn has the potential to fail to provide a stability effect. Instead, Mn interferes with the structure of the original crystal as shown in figure 3.

The addition of Mn can also create significant structural defects or lattice stresses. Impaired crystal structure causes lattice instability, is more susceptible to degradation during cycles and inhibits ion diffusion. This mechanism results in rapid loss of capacity or results in very poor retention [31], [32]. Retention recovery at Mn 0.35 suggests that at this concentration, Mn is likely to successfully stabilize the structure well.

Theoretically, the U-shape phenomenon is closely associated with the structural stability of cathode materials [33], [34]. The coulombic efficiency and capacity retention are highly dependent on the integrity of the crystal structure and the stability of the electrode-electrolyte interface. A decrease in performance at intermediate Mn concentrations (0.2 to 0.3) indicates the possibility of structural instability. This condition can trigger the dissolution of Mn (Mn^{2+}) ions from the cathode into the electrolyte. The dissolved ions and Mn migrate and deposition on the anode, then catalyze the decomposition of the solid electrolyte interphase (SEI) layer. SEI malfunction leads to continuous consumption of electrolytes and activated lithium. Directly lowers coulombic efficiency and labors capacity retention [35].

On the other hand, a significant increase in performance at the Mn concentration of 0.35 indicates that the composition may represent an optimal stability point. In this ratio, Mn is thought to play a role in strengthening the structure of the crystal. The more stable structure effectively suppresses Mn dissolution, maintaining the integrity of the SEI layer in the anode. Thus, resulting in superior efficiency and capacity retention [36].

3.2 Effects of Nickel on Capacity and Retention

Nickel (Ni) plays an essential role as the main electrochemical component that determines the specific capacity of the main electrochemical cathode material. Determine the specific capacity of lithium-ion battery cathode materials, especially in nickel-rich materials. Analysis of both graphs shows a complex and non-linear correlation between Ni concentration and cycle capacity and retention.

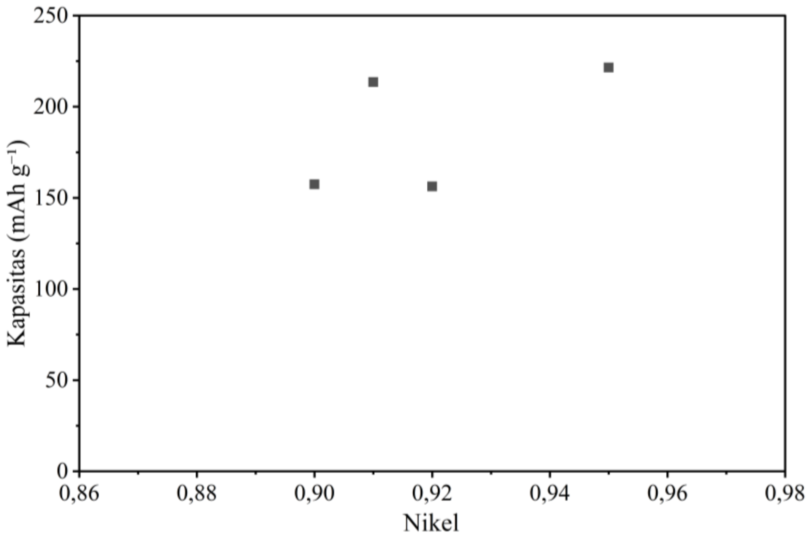

Figure 4 Ni Effect on Capacity (mAh g^{-1})

Based on figure 4, extreme and sudden fluctuations can be seen. The increase in the Ni concentration from 0.90 to 0.91 managed to increase the capacity significantly from 155 mAh g-1 to its peak at 215 mAh g-1. However, the increase in Nickel to 0.92 actually led to a drastic decrease in capacity to 155 mAh g-1. Finally it increased very high again to 220 mAh g-1 at a concentration of Nickel 0.95. This unstable graph pattern indicates that at high Ni concentrations, the performance capacity of the material is highly sensitive to variations in composition or synthesis conditions that cause the capacity to oscillate drastically.

In accordance with the principle that the increase in Ni content will be positively correlated with the high specific capacity potential because Ni acts as an active redox center in charge storage. The Ni principle is applied in a very high capacity of 215 mAh g-1. However, the drastic fluctuation of the drop to 155 mAh g-1 highlights the existence of stability issues in the Nickel-rich material. The decrease in capacity is caused by the mixing of cations in which excess Nickel atoms move to Lithium (Li) in the crystal structure [37]. This displacement effectively inhibits the lithium-ion transfer pathway, reducing the number of available active sites and resulting in significantly lower capacity.

On the other hand, figure 5 shows that at very high Ni concentrations of 0.9 to 0.95, retention shows significant fluctuations. The highest retention rate was 85%, but there was a sharp decline to a low of 68%, before increasing again by 77% to 79%. Indicates that the concentration of Ni is so high that the ability of the material to maintain capacity is very sensitive to small variations in material composition.

Retention fluctuations characterized by decreases and increases are related to the structural stability properties of nickel-rich materials. Although, Ni has a positive effect on specific capacities, the very high concentration of Ni poses a major challenge to the long-term stability of the material. Meanwhile, the decrease in retention is caused by extreme thermal and structural destability. At high Ni levels, the material becomes highly susceptible to reactions with electrolytes, cation migration and phase changes such as the formation of rock-salt phases on the surface during the cycle [38], [39]. All mechanisms aim to accelerate material degradation leading to a drastic decrease in the ability of materials to maintain initial capacity.

An increase in retention that is close to 100% means that at the Ni concentration there is a structural improvement or surface optimization that succeeds in suppressing the degradation mechanism so that retention experiences a slight increase. Overall, it shows that there is a critical limit to Ni high capacity that must be at stake at the expense of cycle stability [40], [41].

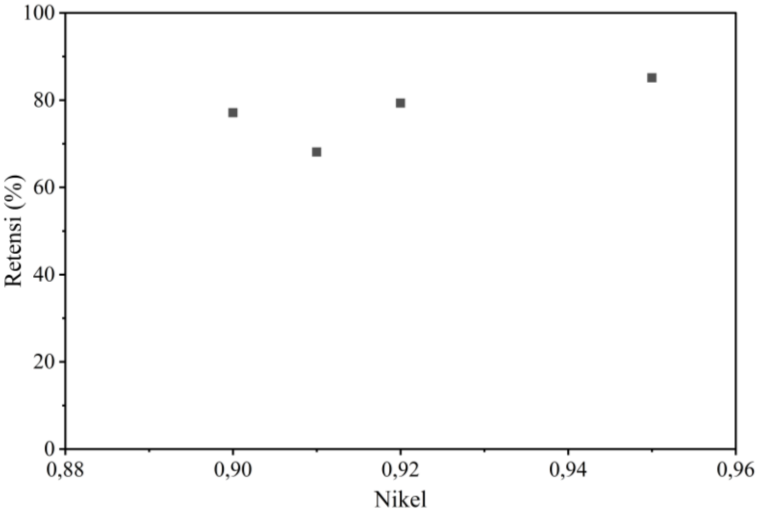

Figure 5 Effect of Nickel on Retention (%).

Theoretically, this phenomenon highlights a fundamental dilemma in Ni-rich cathode materials. The high specific capacity is highly dependent on the redox activity of the Ni^{2+}/Ni^{3+} and Ni^{3+}/Ni^{4+} pairs. Increasing Ni to 0.92 maximizes the number of active species, resulting in the highest capacity. However, the high proportion of Ni, especially the formation of highly oxidative Ni^{4+} species under full delitiation conditions, induces severe structural and interface instability [42], [43], [44].

Very poor retention at Ni 0.91 can be attributed to two main degradation mechanisms [45], [46], [47] : 1) Mixing cations i.e. high Ni content increases the probability of Ni^{2+} ions. Aims to migrate and occupy Lithium sites within the layer structure. This inhibits the Li+ ion pathway thereby increasing the cell's impedance and causing a rapid decrease in capacity during the cycle. 2) Thermal stability and volume change: Ni-rich materials undergo significant lattice volume changes during the Li^{+} intercalation/deintercalation process. This can lead to cracking of particles, loss of electrical contact and unwanted side reactions with electrolytes. This condition continuously leads to fading capacity or poor retention.

3.3 Effect of Cobalt on Coulombic Efficiency and Retention

Cobalt (Co) plays a crucial role as a structural stabilizer in cathode materials. This element directly affects the efficiency and retention of the cycle. The data analysis is shown in the following figure.

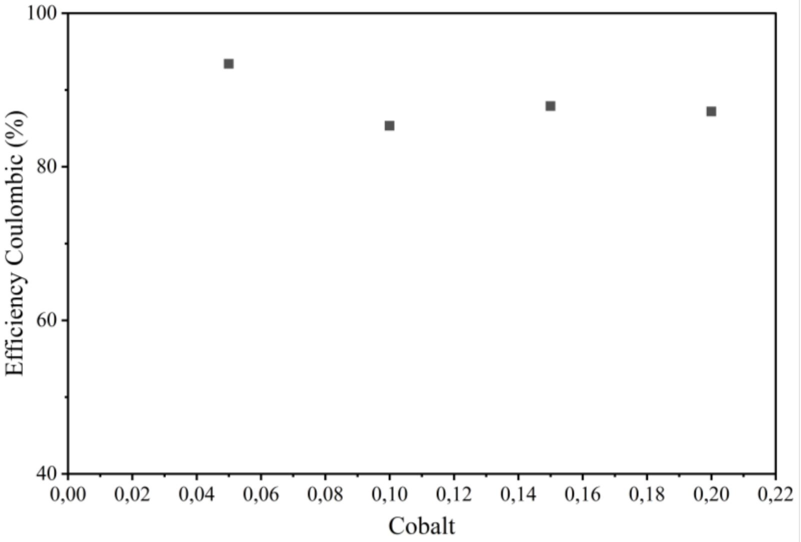

Figure 6 Effect of Cobalt (Co) on coulombic efficiency (%).

Coulombic efficiency (EC) is a key performance parameter in an energy storage system which is defined as the ratio of the charge extracted during the discharge process in a single cycle. A high EC value (close to 100) is highly desirable because it indicates that only a small charge is lost due to side reactions, indicating good cycle reversibility [48], [49]. The data in Figure 6 shows that the highest coulombic efficiency (EC) of 87% to 93% is achieved with the lowest Co concentrations of 0.05 and 0.2. When the concentration of Co is increased by 0.1, there is a significant decrease in efficiency by 85%. An increase in Co concentration from 0.1 to 0.15 did not show a significant improvement but rather efficiency appeared to recover slightly and was stable in the range of 85% to 87%. In conclusion, in the reviewed range the higher concentration of Co implies that the addition of excess Co may trigger parasitic side reactions or reduce the stability of the electrode/electrolyte interface thereby causing a loss of active charge during the cycle.

A more complex pattern observed in figure 7 for Co 0.1 is confirmed as the worst-performing composition with 75% retention. This shows that the concentration of Co 0.1 is very unfavorable for material performance. Theoretically, it is explained that the main function of Co is to suppress the mixing of cations and strengthen the crystal structure [50], [51]. Interestingly, the Co concentration of 0.05 is seen as an optimal balance which indicates a near-ideal peak capacity retention of 98%. Meanwhile, the composition of Co 0.05 shows the most balanced overall performance with a high coulombic efficiency of 93% and excellent retention of 95%. That is, at this concentration Co manages to stabilize the structure and keep the electrode/electrolyte interface passive [52], [53].

The decrease in total performance at Co 0.1 indicates that the stoichiometric ratio is likely to disrupt the grid order without improving it, thus accelerating degradation. On the other hand, the very high retention peak of 98% at Co 0.15 suggests that the optimal concentration for structural stability is pure. The Co in this ratio is most effective at suppressing phase changes and particle cracking thus causing bulk material integration during the cycle although the EC is not as high at the 0.05 composition [54], [55].

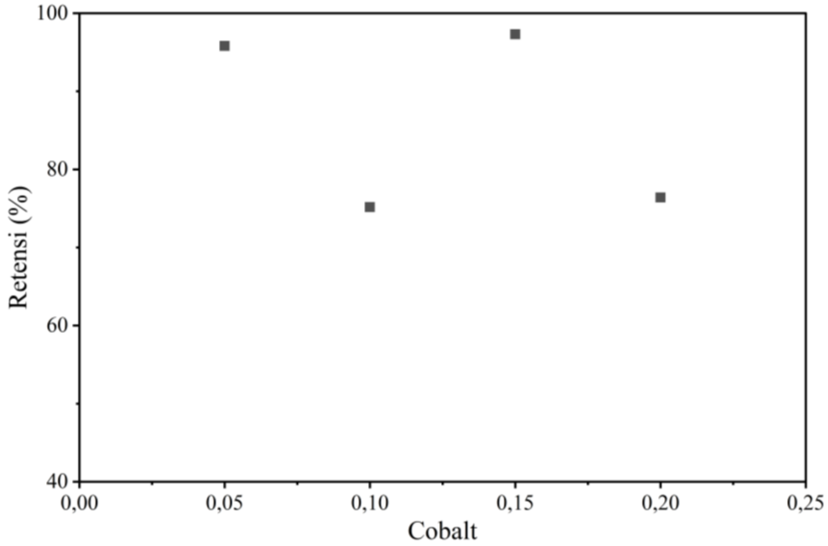

Figure 7 Co’s Influence on Retention.

4. Conclutions

The systematic literature review of this review unequivocally shows that the performance of Light Electric Vehicles (LEV) batteries is divided by specific capacity, coulombic efficiency (EC) and capacity retention is determined based on the complex and non-linear interactions of the NCM (Nickel, Cobalt and Manganese) cathode composition ratio. Manganese (Mn) and Cobalt (Co) function as structural stabilizers with an optimal Mn concentration of 0.35 to the extreme suppressing material degradation and ion dissolution resulting in improved retention and EC performance. In contrast, Nickel (Ni) despite being the main driver of specific capacity is capable of generating high structural susceptibility in Nickel rich materials of 0.90 to 0.95. Performance fluctuations are caused by degradation mechanisms such as cation mixing and thermal instability. Therefore, the fundamental challenge in optimizing NCM cathodes for LEV lies in achieving a balanced trade-off, namely maintaining the high capacity provided by Ni. It aims to ensure long-term life cycle stability through the stability role of Co and Mn.

Nickel was identified as the main driver of battery-specific capacity, where the increase in concentration was positively correlated with high energy potential reaching a peak value of 220 mAh g-1 at a Ni concentration of 0.95. In contrast, Cobalt plays a crucial role as the main structural stabilizer that supports fast charging and discharging performance. For the LEV context, the analysis showed that the Co concentration of 0.05 provided optimal overall performance balance resulting in a high EC of 93% and excellent capacity retention of 95%. Although peak capacity retention reaches 98% at Co 0.15, the 0.05 composition is preferred because it combines strong retention with high EC.

Based on the limitations and focus of the review, there are several things that need to be explored further, especially in the context of LEV. The first focuses on the operational conditions of LEVs, specifically examining the impact of NCM composition on EC, retention and capacity under operational cycle conditions with LEVs such as charging and discharging. The second is about thermal stability, by mapping the performance trade-off between the three main parameters, namely EC, retention and capacity with thermal stability metrics. Third, regarding the impact of coating and surface doping, through the analysis of cathode material modification strategies so that it can intervene and reduce the degradation effects caused by Ni cation mixing and Mn dissolution on performance for capacity and life cycle.

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