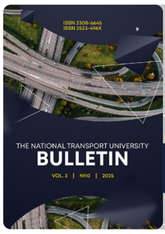

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A new approach to increasing the lifecycle of energy storage for electric vehicle

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Abstract. The article identified the most promising aspects for achieving a significant level of development in lithium battery technology. The purpose of this work was to analyse a new approach to increasing the life cycle of lithium batteries by replacing cobalt with organic electrode material, to demonstrate the operational competitiveness of stable organic electrode materials in lithium-ion batteries, and to determine the advantages of such application. The object of the study was the physicochemical foundations of organic materials that dissolved in the electrolyte of a lithium-ion battery and their transfer to the opposite side of the battery. The research method involved an analysis of the optimal properties of the physicochemical basis of organic materials and cathodes of lithium-ion batteries on an inorganic basis at the electrode level. The article analysed the results of scientific studies devoted to the development of high-performance lithium-ion batteries, mainly using organic electrode materials, namely bis-tetraaminobenzoquinone, composed of carbon, nitrogen, oxygen and hydrogen. It was found that tetraaminobenzoquinone, owing to hydrogen bonds, formed nearly flat sheets, which allowed effective layering and storage of lithium ions and provided a tenfold increase in gravimetric energy density. The article identified the advantages of organic electrode materials in comparison with leading contemporary lithium-ion integrated batteries cathode technologies. The results of the research based on the new organic battery technology made it possible to suggest the potential for a breakthrough in the field of large-capacity batteries and the development of batteries with high charge storage density and rapid charging capability. The article is recommended for specialists in electric transport and manufacturers of electric vehicles, as well as for specialists of operating enterprises carrying out conversions, in particular of trolleybuses with autonomous propulsion

Keywords: battery; cobalt-free cathodes; charging; hydrogen bonding; organic material

Introduction

The issue of saving fuel and energy resources and the use of energy-efficient methods is the most important and acts as a priority direction in the economic policy of the state. The need to develop the road and transport complex is due to the improvement of the technical characteristics of vehicles and the introduction of energy-efficient and resource-saving technologies. This is influenced by the increase in the price of fuels and lubricants for motor vehicles and road machinery; the energy intensity of the country's gross product is almost twice as high as the European one. Therefore, the strategic direction of the state policy for the development of the economic and social sphere is to strengthen energy saving, which ensures high economic efficiency. According to S.V. Voitkiv (2023), a key measure in the implementation of resource-saving structural optimisation is the use of resources, which is based on the implementation of new technological solutions using non-traditional materials and energy sources. Solving energy saving issues when operating electric vehicles requires a special method of energy saving and, accordingly, increasing the service life of energy storage devices for electric vehicles. Scientific discourse focuses on the prospects for improving batteries for electric vehicles.

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Lithium-ion batteries (LIBs) play a crucial role in the decarbonisation of electric transport and energy networks. N.V. Martyushev *et al.* (2023) determined that LIBs depend on expensive, earth-scarce cobalt in the widely used high-energy layered cathodes. Authors revealed the role of lithium deficiency in suppressing the phase transformation of rock salt into a layered structure and crystal growth using multi-scale correlated experimental characterisation and computer simulation of the calcination process. The study resulted in small-sized composites with desirable low anisotropic lattice expansion/contraction during charging and discharging. This provided significant first-cycle coulombic efficiency, 90% capacity retention, and near-zero voltage drop over 100 deep cycles, demonstrating its potential as a trackless cathode for stable LIBs. Using stoichiometry, N.V. Martyushev *et al.* (2023) demonstrated an effective route to structural and morphological tuning of lithium batteries to stabilise cobalt-free cathodes. Moreover, the desired cost-effectiveness was obtained, which was achieved by eliminating additional coating/doping steps, and a promising and cost-effective alternative to cobalt-dependent cathodes was proposed. Therefore, the study addressed the critical need for the development of stable and commercially viable LIBs. M. Mądziel & T. Campisi (2023) highlighted the importance of addressing the scaling and manufacturing challenges associated with cobalt-free cathode materials to enable widespread adoption in commercial batteries. The study summarised the scientific and technical gaps and potential of a variety of cobalt-free lithium-ion cathodes, including layered, spinel, olivine, and disordered rock salt systems. It also predicted the enormous potential of cobalt-free LIBs for sustainable electric vehicle production in the coming decades.

The study by R.V. Bagach (2021) identified the critical design parameters of high-nickel layered oxide cathodes intended for implementation in electric vehicles over the coming decade. It is noted that nickel is of great interest for the production of layered oxide cathodes due to its lower cost, wider availability and lower toxicity than other constituent elements. The study outlined various intrinsic limitations to maximising their energy output. Furthermore, current/new development roadmaps approaching low-cobalt/zero-cobalt chemistries were compared. Attention was paid to the production of materials related to cost reduction and solving practical problems of high-nickel layered oxides for electric vehicles. As a result, a series of stabilisation methods were evaluated for their prospects for achieving aggressive vehicle electrification goals. V. Haydamaka & L. Ivanov (2022) analysed in detail the scientific basis of the synthesis of single-crystal materials and comparative studies between single-crystal and polycrystalline materials. Single-crystal materials have great potential to solve the problems that hinder their polycrystalline counterparts. Industrial methods and equipment have been identified, which are considered in combination with some experience in single-crystal research. As a result, it has been found that future development should focus on simplified production with strict control of particle size and distribution, structural defects and impurities, in order to fully exploit the advantages of single-crystal materials. In this context, the following prospects for single-crystal technology have been considered:

1. Development direction. The favourable properties of single-crystal materials were taken into account and the need to develop a route to single-crystal cathodes for layered oxides with an ultra-high nickel content was emphasised.

2. Synthesis problems. To solve this problem, the molten salt method was recently applied, which included comparative studies of different salts instead of the high-temperature method. According to the results of the study, it was found that the growth of crystal faces can improve the transport of lithium ions in the presence of any type of salt.

3. Further technologies. During the study, it was determined that additional processing procedures, including grinding, sieving and washing, have a significant impact on the electrochemical characteristics of single-crystal materials, as two important steps for obtaining single-crystal materials with well-distributed sizes. It was found that single-crystal materials can take advantage of particle size tuning to maximise volumetric energy density.

4. Electrochemical properties. In order to gain insight into the rational design of cathode materials with thermal and cyclic stability, it is necessary to investigate the relationship between the properties and characteristics of single-crystal materials.

Ensuring that single-crystal materials exhibit optimal properties is crucial, which highlights the necessity of developing reliable strategies for synthesising single-crystal cathodes based on layered oxides with ultra-high nickel content. According to V. Haydamaka & L. Ivanov (2022), the strategies for modifying single-crystal cathodes are at an early stage and require further research. Issues of operational characteristics and resource efficiency, in particular, of traction batteries, are considered in works by W. Li *et al.* (2020) and S. Lee & A. Manthiram (2022). The advantages of replacing inorganic cathodes with organic electrode materials (OEMs) were investigated by P. Poizot *et al.* (2020) and J. Kim *et al.* (2023). The implementation of such technologies is expected to play an important role in achieving global decarbonisation goals and supporting the broader adoption of electric vehicles. The purpose of this work was to evaluate a new method for extending the service life of LIBs by replacing cobalt with organic electrode materials, to illustrate the functional competitiveness of durable OEMs in real batteries, and to determine the advantages of this application.

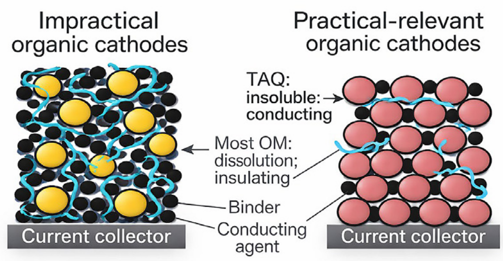
Materials and Methods

The study had a theoretical nature and was conducted within the framework of a qualitative analytical design. The object of analysis was the process of solving the issues of fast charging and longevity of LIBs, while the subject was the properties of OEMs. A literature review was conducted with a focus on cobalt-free cathode materials for LIBs and alternative technologies for replacing cobalt in LIB cathodes. The selection of sources included works by Y. Wang *et al.* (2008), S.W.D. Gourley *et al.* (2020) and A. Zeng *et al.* (2022). Emphasis was placed on the approaches of R. Zhang & L. Ma (2023), who demonstrated that organic materials composed of abundant elements provide high specific capacity due to the dense arrangement of redox centres and low molar mass. Literature was searched through scientific databases such as Scopus, Web of Science, and Google Scholar using keywords such as "cobalt-free cathode", "organic electrode material TAQ", "bis-tetraaminobenzoquinone", "redox-active organic cathode", and "lithium-ion battery cobalt replacement".

The methodology included a systematic critical literature review to identify and assess relevant publications. A content analysis of scientific texts was used for in-depth analysis, employing categorical coding that covered chemical structure, redox-reaction mechanisms, molecular packing, solubility in electrolytes, Li^+ ion diffusion, electronic conductivity, cyclic stability, and energy density at the electrode level. A comparative method was used to contrast the characteristics of TAQ with traditional cathodes Mn (e.g., $LiCoO_2$ (LCO) and $LiNi_{1-x-y}MnxCoyO_2$ (NMC), $LiFePO_4$ (LFP)), particularly in terms of electrochemical efficiency and operational stability. A synthetic analysis combined results from various studies to create a conceptual model of the advantages of TAQ as a cobalt-free cathode material. Special attention was given to the analysis of graphical materials, including diagrams, spectroscopic data (^1H and ^{13}C NMR), and structural schemes presented in the source base of the article. The critical evaluation method allowed for the identification of the limitations of existing organic materials, such as solubility, low conductivity, and the need for large additives, and justified the innovative potential of TAQ due to its properties: virtually zero solubility, high electronic conductivity due to intermolecular interactions, and rapid Li^+ diffusion in the two dimensions (2D)-layered structure. The study was based on an interdisciplinary approach combining elements of materials science, electrochemistry, and environmental chemistry. The methodology used enabled the generalisation of the current state of research and the formulation of conclusions regarding the practical prospects of using TAQ in LIBs for electric transportation.

Results and Discussion

A key avenue for advancing energy-efficient technologies in the transportation sector is the deployment of lithium-ion batteries in electric vehicles. Batteries are designed to store and use electricity that is not used during generation, increasing energy self-sufficiency and independence. It should be noted that LIBs are the predominant energy storage solutions for energy efficiency in electric vehicles. It is modern LIBs that provide high energy density, which ensures sufficient range. Energy density is a crucial indicator for electric vehicles, as it determines the range. Conventional cathodes for LIBs are made of inorganic oxides, particularly Co, Ni, and Mn (LCO, NMC, LFP). Among these, cobalt presents serious limitations due to its rarity and significant social costs (e.g., child labour). The complete elimination of cobalt has been difficult because cobalt-free oxide cathodes experience insufficient cycling or capacity (Wang *et al.*, 2008). In fact, electric vehicles currently use mainly cobalt-based batteries. But the growth of the global electric vehicle fleet is virtually impossible without the development of cobalt-free technologies, as noted by A. Zeng *et al.* (2022). Articles by J.-M. Tarascon (2010), D. Larcher & J.-M. Tarascon (2015) and B.M. Spears *et al.* (2022) identified an organic substance that could replace the environmentally harmful cobalt currently widely used in LIBs. Redox organic materials derived entirely from earth-based elements represent just such an opportunity. TAQ is a distinct organic compound, or TAQ, composed of carbon, nitrogen, oxygen, and hydrogen. Its structure, a sequence of three connected hexagons, is similar to graphite, which is often used in battery anodes. TAQ is characterised by the fact that it forms nearly flat sheets through hydrogen bonding, which allows it to efficiently layer and store lithium ions (Mishchenko, 2024). From a design perspective, small organic molecules offer high specific capacity due to the compact arrangement of redox centres and their low molar mass compared to redox polymers or framework materials. However, discrete molecules typically have low bulk conductivity and are often soluble in battery electrolytes, leading to poor utilisation of redox sites, low charge-discharge rates, and poor cycling stability (Lu *et al.*, 2018; Lu & Chen, 2020). These problems are routinely addressed by the addition of conductive and/or stabilising polymer additives, often exceeding 50 wt%, which significantly reduces the effective capacitance, making the electrodes impractical (Luo *et al.*, 2017). Consequently, there remains considerable enthusiasm for the fabrication of inherently insoluble and conductive OEMs. The goal is to achieve high specific capacitances at appropriate cathode potentials exceeding 2.0 V for LIBs, as shown in Figure 1.



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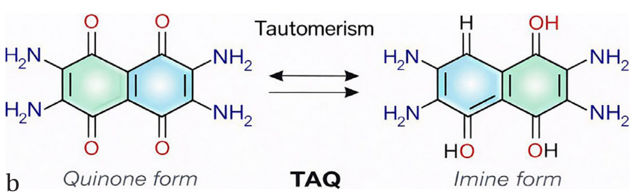

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Figure 1. Characteristics of TAQ

Source: R. Zhang & L. Ma (2023)

Poly(acetylene), poly(pyrrole), poly(thiophene) and poly(aniline) are omitted because they function through anion incorporation rather than Li^+ incorporation. Asterisks indicate a rapid capacity decline during the first few cycles, mainly as a result of dissolution. TAQ, a molecule consisting of fused conjugated elements with a rigid layered arrangement in the solid state, has been found to be an effective component for OEMs used in LIB cathodes, exhibiting properties such as fast charging, high energy density, and extended cycle life (MIT team develops…, 2024). The defining feature of TAQ is its tightly packed structure, which includes a conjugated framework filled with redox-active carbonyl (C = O) and imine (C = N) groups. These are the active sites. The TAQ molecule exhibits strong intermolecular hydrogen bonds and donor-acceptor ϖ–ϖ interactions, which render it insoluble in standard battery electrolytes. At the same time, these interactions contribute to the extended electron delocalisation within the molecule, leading to high bulk conductivity, as shown in reference (Zhang & Ma, 2023). Due to its small solid-state packing, TAQ exhibits very low solubility in common organic solvents and battery electrolytes. A notable observation is that when TAQ is heated in deuterated N,N-dimethylformamide at 120°C for extended periods of time, including overnight, it becomes virtually insoluble. This conclusion is supported by the fact that the 1H and 13C spectra of the supernatant show no detectable signals corresponding to TAQ. Due to its small solid-state packing, TAQ exhibits very low solubility in common organic solvents and battery electrolytes. The minimal solubility of TAQ, which is maintained even at elevated temperatures, is strikingly different from that of other OEMs used in lithium-ion batteries (LIBs). This characteristic is crucial for achieving extended battery life in these batteries (Zhang & Ma, 2023). Due to these specific characteristics, electrodes containing a minimum of 90 wt% TAQ are able to store charge reversibly and operate safely for more than two thousand cycles. This is a notable improvement, especially when compared to the persistent electrode dissolution problems often observed in established OEMs (Fig. 1). The layered structure characteristic of TAQ molecules in two dimensions 2D facilitates the easy movement of Li^+-ions – both input and extraction – within the layers. Thus, extraordinary capabilities are achieved with full charging in just three minutes. In addition, the optimised electrodes demonstrate excellent performance. They maintain this quality even when operating with significant planar loads, reaching 16 mg/cm^2. The resulting capacity area, up to 3.52 mAh cm^{-2}, rivals that observed in commonly used LIBs. This fully demonstrates the potential of TAQ for practical applications in the field of LIBs (Zhang & Ma, 2023). This metal-free, layered organic material, designed for use as a cathode in Li-ion batteries, offers superior performance. It facilitates the intercalation of Li^+ ions and achieves a higher energy storage capacity within a significantly reduced charging duration, compared to the established inorganic battery technologies. AQ electrodes, when composed of a pure substance, demonstrate commendable durability, enduring no fewer than 50 cycles. These cycles are executed under a constant-current constant-voltage (CCCV) regime, set at a rate of 0.2 C for charging and 0.125 C for discharging. The experiments conducted by R. Zhang & L. Ma (2023) involved a complete depletion of capacity, reaching a 100% depth of discharge (DOD). After this rigorous testing, the electrodes retained 75% of their original capacity, with an average coulombic efficiency (CE) exceeding 98% (Fig. 2).

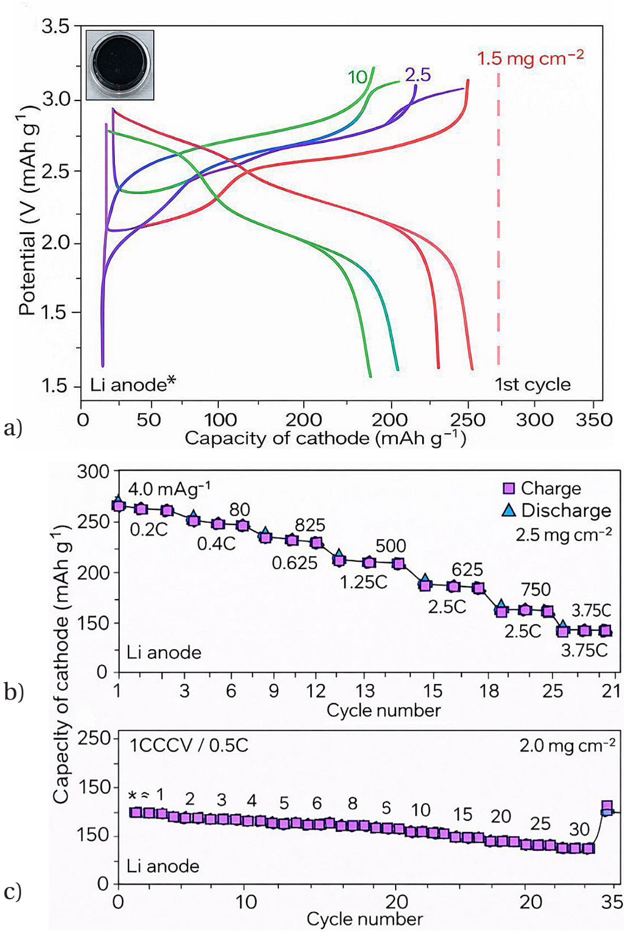

Figure 2. Characterisation of clean TAQ electrodes
Source: R. Zhang & L. Ma (2023)

The cycling behaviour demonstrated by these pristine factory standard electrodes surpasses all previous records. This remarkable performance is indicative of the efficient ion diffusion and charge transfer characteristics of TAQ, as well as its almost complete resistance to dissolution in standard battery electrolyte solutions. In fact, although the claimed voltage of TAQ is lower than that of traditional inorganic cathodes, the gravimetric specific energies observed in the electrode itself in the C range exceed those of even the most advanced inorganic cathodes. The energy density achieved at the electrode level with TAQ cathodes exceeds that of many alternative composite cathodes. These include single crystal NMC811 (NMC811-sc), as well as the conventional polycrystalline variants NMC811 and NMC111. Furthermore, TAQ cathodes outperform even advanced cobalt-free oxides. This advantage, which provides an increase of at least 20-30%, is maintained over a wide range of charge/discharge rates, extending from approximately 0.1 C to 10 C (Zhang & Ma, 2023). Moreover, TAQ outperforms LiFePO4 graphite-coated cathodes (LFP-GC) in terms of gravimetric energy density, achieving this at a charging rate that is at least ten times faster (MIT team develops…, 2024; Chen *et al.*, 2024). It should be noted that although the nominal voltage of TAQ is lower than that of conventional inorganic cathodes, the gravimetric specific energies at the electrode level for TAQ cathodes in the range of C values exceed even those of optimised inorganic cathodes. As the analysis showed, cobalt, a critical metal used in LIBs, is predominantly obtained from low-concentration by-products of nickel and copper mining, making it the most valuable metal in this context. Given this, the necessity and feasibility of developing cobalt-free materials and substituting them with organic materials for LIBs have been carefully evaluated. Therefore, increasing efforts to develop cobalt-free cathode materials, particularly through the use of layered organic electrodes with advantageous properties, presents a promising solution to the issue of cobalt scarcity. This approach could significantly enhance the performance of LIBs and contribute to their widespread adoption, especially in electric vehicles.

Based on a comparison of results reported by various authors and the present study, several trends were identified. First, it was evident that cobalt-free cathode materials, particularly organic alternatives, show promising potential for replacing cobalt in LIBs, as highlighted in the studies by S. Lee & A. Manthiram (2022). Depending on the cathode composition, 80-200 g of cobalt per kWh is added to commercial LIBs. Cobalt has long been an important element in the layered oxide cathode family, from the parent LCO composition to the NMC family with various Ni/Mn/Co ratios. The paper also considered the possibility of replacing Co with Ni and Mn as a viable way to increase the usable specific capacitance by utilising $Ni^{2+}/^{3+}$ and $Ni^{3+}/^{4+}$ redox centres while maintaining the advantages of Co, such as good electronic conductivity and low Li/Ni miscibility for easy ionic conductivity. Therefore, layered oxides with increasing Ni content are gradually being introduced. At the limit of Ni content is the archetypal high-energy material LiNiO2 (LNO), which provides an average voltage of ~3.8 VLi (V vs Li/Li) and a specific capacity of up to ~240-250 mAh^{+}. However, increasing the Ni content in layered oxides also increases surface, structural and thermal instabilities, which negatively affects battery life and safety. At higher lithium extraction rates at high state of charge (SoC), layered oxides with high Ni content undergo a phase transformation (H2 → H3), which causes large anisotropic compression and collapse of the layered structure. It was found that during thermal retreat, layered oxides with high Ni content experienced a larger exothermic energy release at a lower initial temperature, which compromised battery safety. Rational compositional designs and material engineering strategies on high-Ni oxides, such as surface coatings and electrolyte modifications, have achieved some success in overcoming these instability issues. Thus, high-layer oxide cathodes remain an ideal choice for electric vehicles due to their high energy density, sufficient cycle life and rate performance, and long-standing large-scale synthesis infrastructure (Lee & Manthiram, 2022). Although Fe- and Mn-based cathodes have lower energy densities, they are attractive alternatives to Co- and Ni-based cathodes for electric vehicles due to the abundance of raw materials. LFP is the most ideal Fe-based compound, providing decent energy density at the material level (~3.4 V Li, ~160 mAh g^{-1}). Combined with the facile phase transformation kinetics with nanoparticles and low charge cut-off voltage (~3.6 V), LFP has demonstrated exceptional cycle life and rate capability, as well as robust resistance to extreme operating conditions. As a result, a low-Ni cathode, HE-N50, was successfully developed to remove Co from a commercial ternary layered cathode based on a sophisticated concentrated doping strategy This strategy provided outstanding structural and thermal stability, leading to improved cycling performance both at room temperature and under thermal stress conditions. Furthermore, the reduced use of Ni and zero use of Co can reduce the cost of the cathode compared to the basic NMC materials while maintaining high energy density. This work also opened up opportunities for optimising low-NiMn cathodes, including Li-excess cathodes, through controlled combinations of several elemental components.

The article by S.W.D. Gourley *et al.* (2020) raised the need to develop cobalt-free cathode materials for LIBs. LIBs are a straightforward solution for recovering cobalt, but the technical challenges of disassembling the battery pack and the mixed metal components limit its use. A more efficient and long-term solution for a sustainable future for LIBs is the development of cobalt-free cathode materials. To achieve a significant increase in energy density, the cathode must be combined with a high-capacity anode, specifically silicon or lithium metal. Engineering innovation is needed to optimise cell production for these new technologies. As noted in the article, LIB technology for electric vehicles is currently dominated by two main cathode compositions – layered $LiNi_{1-x-y}KoxElO_2$, $x + y < 0.2$ (NCA) and $LiNixMinnesotayKozO_2$, $x + y + z = 1$ (NMC). Among NMC-type compositions, LiNi1/3Minnesota1/3Ko1/3O2 (NMC111) is the best known, characterised by its stability and safety. Taking into account the increase in power (at 4.3 V versus the upper limit of Li/Li) and low cobalt content, a replacement for NMC111 (~160 mAh g^{-1}, 20.4 wt% Co) was developed with LiNi0.6Minnesota0.2Ko0.2O2 (NMC622, ~180 mAh g^{-1}, 12.2 wt% Co) and LiNi0.8Minnesota0.1Ko0.1O2 (NMC811, ~200 mAh g^{-1}, 6.1 wt% Co) (Myung Ni-rich cathodes also suffer from increased sensitivity to moisture. These cathodes exhibit Li/Ni^{+2+} cationic mixing and electrolyte side reactions (solvent oxidation from Ni^{4+}). They are also characterised by phase transitions to spinel and rock salt structures. Furthermore, they exhibit oxygen evolution at elevated temperatures and stresses (Gourley *et al*., 2020). This study also proposed a promising approach to addressing these issues: synthesising NMCs in the form of micron-sized single-crystal particles. The single-crystal morphology has a minimal number of grain boundaries and, therefore, is capable of mitigating particle cracks and side reactions with the electrolyte. It was found that one of the most promising approaches to developing cathodes for LIBs with less cobalt dependence was the improvement of multilayer LiNi with Ni-xMxO$_2$ (M = Mn, Al, and/or Co) materials. Accordingly, the main barriers hindering the further adoption of cobalt-free layered cathodes over existing materials in modern lithium-ion batteries (LIBs) are thermal instability. This study confirms the feasibility of replacing cobalt with nickel in NMC and NCA-type compositions, which has proven to be an effective method for stabilising Ni^{2+} ions in the transition metal layer, thereby reducing the degree of cation mixing. High-temperature performance (≥50°C) can improve the rate for cobalt-free formulations; however, operating above 30°C may accelerate structural failure.

Therefore, the use of modern low-cobalt materials (e.g., NMC622, NMC811, NCA) is not a sufficient mitigation strategy, as cobalt supply shortages may arise in the near future depending on the sales situation of electric vehicles. S.W.D. Gourley *et al.* (2020) noted that, due to their high energy density, layered transition metal oxides based on $LiNiO_2$ have attracted significant research efforts. A cation doping strategy was considered, which can be combined with morphology control (e.g., individual crystals to suppress cracks). Moreover, the doping strategy can also be combined with coatings that improve interparticle conductivity, provide a protective barrier against electrolyte side reactions, suppress oxygen production, and adjust the oxide packing structure to suppress phase changes. Research in this area has provided the most practical and immediate path to the use of cobalt-free cathodes. On the other hand, cationically disordered rock salt cathodes represent a new class of materials with high energy density (up to ~1,000 Wh kg^2). The results of J. Song *et al.* (2016) demonstrated that applying an ultrathin, highly graphitic carbon coating to LiFePO4 significantly enhances electronic conductivity and reduces the Li^+ diffusion path, enabling excellent rate performance and cycling stability even at high currents and low temperatures. In the present study, TAQ also outperforms traditional LFP-GC in energy density, with at least ten times faster charging speed, without requiring additional conductive additives due to its own high electronic conductivity, attributed to hydrogen bonding and ϖ–ϖ interactions. Thus, while both approaches aim to overcome the low conductivity of LFP, TAQ offers a more radical solution – a complete shift away from inorganic cathodes and cobalt, providing higher capacity with minimal additives and a significantly longer lifespan. In the work of C. Barchasz *et al.* (2013), the focus was on ether-based electrolytes for lithium-sulphur batteries, where the key issue is the dissolution of polysulfides, leading to the "shuttle effect" and rapid capacity degradation during cycling. In contrast, the key achievement of TAQ in this study is its virtually zero solubility in standard lithium-ion battery electrolytes, due to strong intermolecular hydrogen bonds and dense packing, which completely prevents material migration and short circuits, allowing for over 2,000 stable cycles.

Based on the conducted analysis, it has been determined that the potential for replacing cobalt with other organic materials or avoiding reliance on cobalt in LIBs is both feasible and promising. Fe- and Mn-based cathodes, although having lower energy densities, present an attractive alternative to Co- and Ni-based cathodes. Therefore, replacing Co with Ni and Mn has been proposed as a viable way to increase the specific capacity of LIBs. Furthermore, as an alternative to substituting Co with Ni, an ideal mixture of LiFePO4 (LFP) has been proposed, which provides a respectable energy density at the material level (~3.4 V Li, ~160 mAh g^{-1}). LFP remains a viable and cobalt-free alternative as long as the energy density at the cell level is adequate. It is noteworthy that the electrical conductivity of TAQ is comparable to that of LCO and modern NMC, and approximately five orders of magnitude higher than that of LFP. These favourable properties of TAQ enable the production of electrodes with minimal or no additives. Equally important is that TAQ provides a higher gravimetric energy density than graphite-coated LiFePO4 (LFP-GC) cathodes, with a charge rate at least ten times higher. In terms of energy density, TAQ offers at least 20-30% higher energy density at the electrode level compared to most monocrystalline oxide composite cathodes, commercial polycrystalline cathodes, and even modern cobalt-free oxides. The proposed method may reduce or even eliminate the need for cobalt, leading to the development of a new generation of LIBs.

Conclusions

The research has thus identified a cobalt replacement: a layered organic electrode. This material has properties that are important for excellent battery performance. Its excellent electrical conductivity, significant storage capacity, and absolute insolubility contribute to the smooth intercalation of Li^+ ions. It rivals the capabilities of traditional inorganic lithium-ion battery cathodes, matching them in all key performance indicators at the electrode level. It is worth noting that the results demonstrate the practical viability of stable organic electrode materials in the field of LIBs, highlighting their functional advantages. TAQ electrodes also have the significant advantage of offering a higher volumetric energy density compared to similar LFP electrodes. The author notes that TAQ offers significant advantages over the common cathode technologies for LIBs currently available. The primary pathway for organic materials to degrade is through their dissolution in the battery electrolyte. The dissolved material then migrates to the opposite side of the battery, ultimately leading to a short circuit. The author believes that by making the material completely impermeable to dissolution, this phenomenon is prevented, allowing for over 2,000 charge cycles with little degradation. It should be noted that the material cost of assembling these organic batteries can be approximately one-third to one-half the cost of cobalt batteries. Overall, the findings indicate that the development of cobalt-free organic cathodes, particularly with TAQ, could revolutionise LIB technology, offering enhanced performance and sustainability for future energy storage solutions. Further research should focus on optimising manufacturing processes for the production of cobalt-free organic cathodes, enhancing their stability at high temperatures, improving their durability and ensuring the cost-effectiveness of large-scale production, as well as on refining electrolytes to maximise their compatibility with new materials.

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Conflict of Interest

None.

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Новітній підхід щодо збільшення життєвого циклу енергонакопичувача для електричного транспортного засобу

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Анотація. У статті визначено найбільш перспективні аспекти для досягнення значного рівня розвитку технології літієвих батарей. Метою роботи було проаналізувати новий підхід до збільшення терміну служби літієвих батарей шляхом заміни кобальту на органічний електродний матеріал, продемонструвати експлуатаційну конкурентоспроможність стабільних органічних електродних матеріалів у літій-іонних батареях, а також визначити переваги такого застосування. Об'єктом дослідження стали фізико-хімічні основи органічних матеріалів, які розчиняються в електроліті літій-іонної батареї та їх перенесення на протилежний бік батареї. Метод дослідження полягав в аналізі оптимальних властивостей фізико-хімічної основи органічних матеріалів і катодів літій-іонних батарей на неорганічній основі на рівні електродів. У статті проаналізовано результати наукових досліджень, присвячених розробці високопродуктивних літій-іонних батарей, переважно з використанням органічних електродних матеріалів, а саме біс-тетраамінобензохінону, що складається з вуглецю, азоту, кисню та водню. Було встановлено, що тетраамінобензохінон завдяки водневим зв'язкам утворює майже пласкі листи, які дозволяють ефективно шарувати та зберігати іони літію, забезпечуючи десятикратне збільшення гравіметричної густини енергії. У статті визначено переваги органічних електродних матеріалів порівняно з провідними сучасними технологіями катодів інтегрованих літій-іонних батарей. Результати дослідження на основі нової органічної технології батарей дали змогу запропонувати потенціал для прориву в галузі великоємкісних батарей та розробки акумуляторів із високою густиною зберігання заряду та можливістю швидкого заряджання. Статтю рекомендовано для спеціалістів електричного транспорту та виробників електромобілів, а також для фахівців експлуатаційних підприємств, які здійснюють переобладнання, зокрема тролейбусів з автономним ходом

Ключові слова: акумулятор; катоди без кобальту; заряджання; водневі зв'язки; органічний матеріал