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The electrochemical route to sustainable transport

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The electrification of mopeds is a growing concern in urban transportation. Due to their intended use, they represent a prime area for implementing alternative energy storage solutions. Recent research has focused on the use of metal sulfides as anode materials in sodium-ion cells, as well as on carbon materials derived from biomaterials for use in electrochemical supercapacitors. Capacitive properties of these materials were evaluated using techniques such as galvanostatic charge-discharge (GCD) and cyclic voltammetry (CV). The cycling tests demonstrated high reversibility of reactions and strong specific capacitance, indicating good electrochemical performance. GCD analysis of sodium-based systems revealed high initial potentials and efficiency exceeding 90%, suggesting their suitability for long-term applications. Additionally, tests of supercapacitors indicated pseudocapacitive behaviour, further confirming the effectiveness of the studied materials. Overall, the results highlight the strong potential of sodium-ion technologies for energy storage, particularly in applications that require durability, such as electric mopeds.

Key words: *energy consumption, metal sulphides, scooter, sodium-ion cells, sustainable transport*

1. Introduction

Ongoing urbanization, the growing population in metropolitan areas, and increasing congestion of road infrastructure pose significant challenges in ensuring sustainable transport. The rise in individual mobility – driven by dynamic economic development and increasing affluence of societies – has led to a steady increase in the number of vehicles operating on public roads. It is estimated that by 2050, the global number of motor vehicles could double [20]. At the same time, transportation remains one of the primary sources of greenhouse gas emissions, particulate matter, and nitrogen oxides, which impact both the global climate and local air quality [4, 18].

According to the European Environment Agency, the transport sector currently accounts for approximately 30% of the European Union's total energy consumption. It generates 20–25% of total CO_2 emissions, 10% of PM10, and as much as 45% of NO_x emissions [3]. A significant portion of these pollutants is concentrated in densely populated urban areas, contributing to the increased incidence of cardiovascular and respiratory diseases. The World Health Organization (WHO) reports that 90% of the urban population breathes air that exceeds permissible pollution levels, resulting in increased mortality due to cancer, cardiovascular, and pulmonary conditions [24].

In view of these circumstances, the development of electromobility – including L-class single-track vehicles – is becoming one of the key solutions for reducing emissions and improving urban quality of life [11]. A particularly prominent role within this segment is played by electric mopeds and motorcycles, which, in contrast to internal combustion vehicles, do not emit toxic compounds and are characterized by lower energy consumption, reduced operating costs, and a favorable acoustic profile.

According to, the latest Mordor Intelligence report [14], the global market value of electric scooters and motorcycles in 2024 was estimated at USD 38.6 billion, with a projected Compound Annual Growth Rate (CAGR) of 11.1% between 2024 and 2029 (Fig. 1). The fastest market growth is observed in Asia-Pacific countries – especially China, India, and Indonesia – where two-wheelers constitute a primary mode of daily transportation represent a dominant mode of daily transportation.

Fig. 1. Forecasted compound annual growth rate (CAGR) of the electric scooter and motorcycle market by global region, 2025–2030 [14]

In Europe, an increasing number of cities are implementing sustainable mobility strategies that promote the use of light electric vehicles by introducing low- and zero-emission zones, offering free parking, or allowing access to bus lanes. This trend is also evident in Poland, where the number of registered L1e-B class single-track vehicles, as well as those offered through vehicle-sharing schemes, continues to grow.

Despite the rapid advancement of electric drive technologies, energy storage remains a significant challenge. Batteries, as a key component of electric vehicles, are still characterized by limited energy density, relatively high mass, and substantial environmental impact during both production and disposal stages. Breakthrough solutions in battery cell technologies – combining high durability, safety, low unit cost, and reduced dependence on critical raw materials – are still lacking. In parallel with electrification, research is continually being conducted into the development of vehicle powertrains including improving combustion processes in conventional engines and the use of hydrogen fuels [15, 22].

With the growing trend toward electrification of urban transportation, electric mopeds are emerging as a key area for implementing alternative energy storage solutions. Among these, sodium-ion cells represent a promising and cost-effective alternative to traditional lithium-based batteries. Environmental regulations, limited lithium resources, and rising market prices are driving the search for efficient and sustainable energy sources, making sodium-ion technology a compelling candidate. These cells are gaining significant attention from researchers and technologists due to their potential for widespread adoption. Recent studies have focused on the use of metal sulphides as viable anode materials in Na-ion cells, as well as on carbon materials derived from biomaterials for use in electrochemical supercapacitors. This information serves as the foundation for this work, which aims to evaluate selected power sources for scooters used in the city.

The study introduces an eco-friendly and low-energy fabrication approach that employs locust bean gum as a natural binder for sodium-ion electrodes. For lignin-based capacitor materials, we utilised a simplified synthesis route, highlighting the potential of various sustainable methods in electrochemical energy storage.

2. Literature review

A review of the scientific and technical literature reveals a growing focus on the energy and environmental efficiency of single-track vehicles, including L1e-B class electric scooters, when operated under real-world conditions. Particular attention is given to studies that encompass not only energy consumption but also operational constraints and the life cycle of the vehicle and its key components.

In the study by [7], a comparative analysis was conducted of energy consumption and pollutant emissions generated by electric scooters and their conventional counterparts in urban environments, under actual traffic conditions. Based on field measurements, the average energy consumption of an electric scooter was determined to be 2.8 kWh/100 km, which is nearly eight times lower than the energy equivalent of fuel consumption for an internal combustion vehicle. The authors also observed significantly lower CO_2 emissions (14.17 g/km compared to 31.81 g/km), as well as more than a sixfold reduction in operating costs. A notable observation included the higher average acceleration of the electric scooter and lower speed variability during operation, both of which positively influence drivetrain efficiency in urban settings.

The issue of energy consumption throughout the full life cycle of a vehicle was thoroughly addressed in a study by [19], which conducted an LCA (Life Cycle Assessment) for an electric scooter used in a sharing system. The authors reported an average energy consumption of 0.034 kWh/km (3.4 kWh/100 km), which, assuming a total mileage of 50,000 km, corresponds to an energy usage equivalent to 1.25 full battery discharge cycles. The study demonstrated that the greatest environmental burden arises not from the use phase, but from the production and replacement of the energy storage system. This highlights the crucial role of battery durability and energy efficiency in evaluating the total environmental impact of electric vehicles.

From a cost and operational perspective, the study by [8] provides an important contribution. It presents an optimized Total Cost of Ownership (TCO) model for light electric two-wheelers, accounting for variable local conditions such as topographical route profiles, load characteristics, charging infrastructure availability, and type of use (private, fleet, or municipal). The analysis suggests that drivetrain configurations and battery specifications should be carefully tailored to real-world usage conditions. The application of standardized systems may lead to a substantial decline in energy efficiency and increased operational costs.

In the context of the vehicle's complete life cycle, a less frequently addressed but highly relevant issue is the management of used battery packs. Eduardo et al. (2025) [2] conducted a comparative analysis of several "end-of-life" scenarios for batteries used in electric scooters, encompassing both mechanical and chemical recycling methods, as well as secondary use in low-voltage energy storage systems. The study concluded that a properly selected end-of-life strategy for batteries can significantly reduce the vehicle's environmental footprint and lessen its dependency on critical raw materials, such as lithium, nickel, and cobalt, whose availability and prices are subject to high market volatility.

3. Methodology

The systems under investigation were analysed through cyclic voltammetry using the G 1000 Potentiostat/Galvanostat/ZRA from Gamry Instruments (USA). The voltammograms obtained from these tests provided insight into the reversibility of redox processes within the cells and the cyclic stability of the capacitors.

To evaluate the specific capacity and initial coulombic efficiency of the tested systems, galvanostatic charge-discharge experiments were conducted using the ATLAS 0691 MBI testing unit (Atlas-Sollich, Poland). These assessments were conducted under a range of current densities.

The specific energy values for each system have been calculated, enabling their application analysis.

4. Electrochemical analysis of selected power sources

4.1. Na-ion cells with highly efficient anodes

The electrode material incorporates one of three base compounds: CuO, SnS [16], and CoS_2. In each system, the electrolyte used is a 0.8 M solution of $NaPF_6$ in EC: DMC (1:1). An aqueous solution of LBG was employed as the binder. Acetylene black (AB) was used as the conductive additive in the analysed systems.

Galvanostatic curves recorded at a current density of 10 mA/g exhibit distinct plateau regions (Fig. 2).

These plateaus correspond to processes occurring during cell operation, which are the insertion of sodium ions into the anode material and the conversion of the active material. Both processes are reversible. The plateau appears at potentials of approximately 2 V, 1.5 V and 0.5 V. The plateau observed at the lowest potential (0.5 V) corresponds to the decomposition reaction of copper oxide into metallic copper [1].

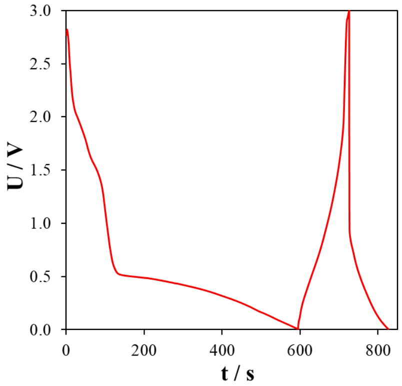


Fig. 2. Graph for an CuO Na-ion half-cell GCD for a current density of 10 mA/g

Galvanostatic charge/discharge testing at a current density of 50 mA/g indicates sustained high reversibility of the intercalation and deintercalation processes (Fig. 3). The observed plateau regions correspond to cyclically occurring reactions during cell operation.

a)

b)

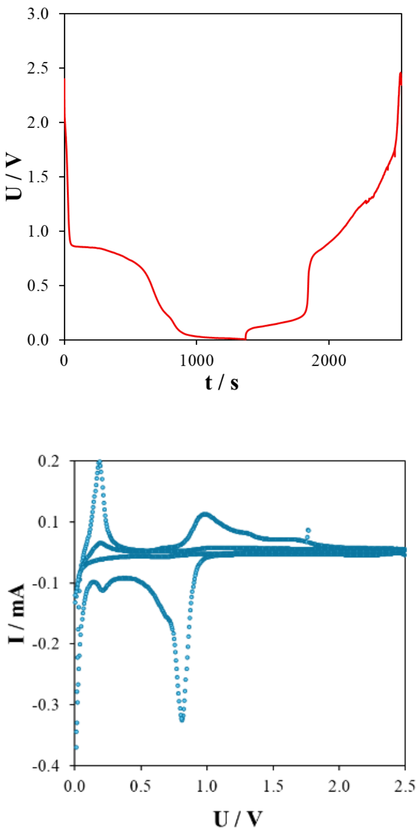


Fig. 3. Graphs for an *SnS* Na-ion half-cell (a) GCD for a current density of 50 mA/g; (b) cyclic voltammetry at a scan rate of 0.5 mV/s

The specific capacities of the analysed material reached 935 mAh/g during sodiation and 482 mAh/g during desodiation in the first cycle. These values decreased to approximately 295 mAh/g by the fifth cycle. At the same time, the coulombic efficiency of the system stabilized above 95% after the fifth cycle. This system demonstrates satisfactory cycling stability and high efficiency in the reversible electrochemical processes.

The cyclic voltammetry curves of the analysed system indicate morphological changes occurring during the first cycle. These changes are associated with electrochemical reactions taking place during cell operation and with the formation of a passivation layer on the electrode surface [23]. The peaks observed in the first cycle do not reappear in subsequent cycles. However, the following cycles exhibit high reproducibility.

The experimental tests with CoS_2 material began with subjecting the system to galvanostatic charging/discharging with a current of 50 mA/g. The capacity for the sodium ion insertion cycle was 1611 mAh/g, while for disinsertion, it reached a value of 867 mAh/g.

During this cycle, two plateaus were observed (Fig. 4). The first occurred during cell charging at a potential of 1.051 V, and the second during discharging at a potential of 1.78 V.

a)

b)

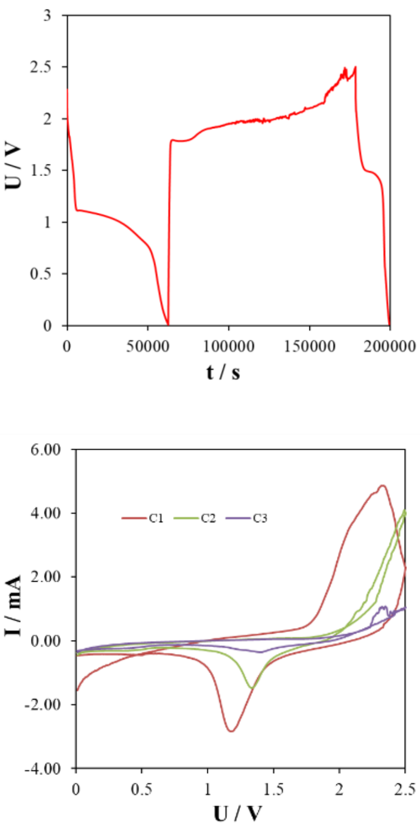


Fig. 4. Graphs for an CoS_2 Na-ion half-cell (a) GCD for a current density of 50 mA/g; (b) cyclic voltammetry at a scan rate of 0.5 mV/s

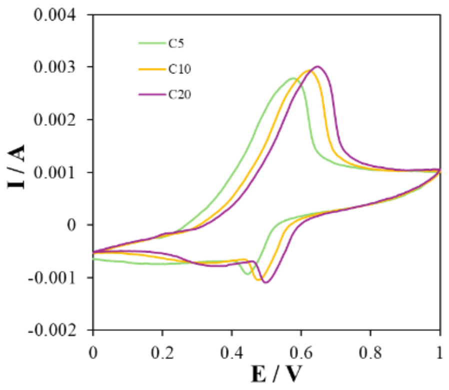
The next stage of the research involved subjecting the system to cyclic voltammetry at a scanning rate of 0.5 mV/s (Fig. 4b). As can be observed, with each subsequent cycle, the intensity of the anodic and cathodic peaks decreases. This indicates lower capacity values compared to the first cycle, as well as decreasing reversibility of the process.

In the first cycle, a reduction peak was observed at a potential of 1.15 V, corresponding to conversion and melting reactions, respectively. During the conversion reaction, a sulphur compound is formed with metallic sodium, while the active material of the electrode is reduced to metallic cobalt. As a result of the melting reaction, an alloy is formed between sodium and cobalt, which can lead to the accumulation of a significant amount of sodium cations on the electrode surface and thus an increase in the volume of the electrode material.

4.2. Bio-based capacitor

Figure 5 shows the CV curves for the 5th, 10th and 20th cycles of operation of the lignin-based capacitor. The preparation method followed the procedure reported in [9]. The shape of the curves deviates from a perfect rectangle, which may indicate the presence of pseudocapacitive processes occurring in parallel with typical ion adsorption or limitations in charge transport in the pores of the material [6]. However, the observed curves indicate good reversibility of the electrochemical reactions and a specific capacitance of 63 F g^{-1}. Slight changes in signal intensity across successive cycles indicate high cyclic stability of the tested material, confirming its potential for long-term use in electrochemical capacitors.

a)



b)

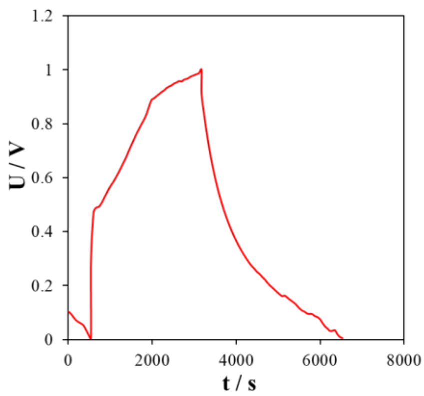


Fig. 5. Graphs for an lignin-based electrochemical capacitor (a) cyclic voltammetry at a scan rate of 10 mV/s; (b) GCD for a current density of 50 mA/g

Additionally, galvanostatic charge-discharge (GCD) measurements were performed at a constant current of 10 mA/g. The obtained curve does not show a perfectly linear course, which may also indicate the participation of pseudocapacitive phenomena. The small voltage difference between the end of charging and the beginning of discharging confirms the low internal resistance of the system. At the same time, the long discharging time indicates good charge storage capacity [5].

The results obtained by CV and GCD methods indicate the favourable electrochemical properties of the lignin-derived material and its suitability as an electrode component in capacitors [10].

5. Power values of the obtained devices

To accurately assess the energy parameters of the devices obtained (Table 1), the energy values were normalized to the mass of the active electrode material. In the case of Na-ion cells, the specific energy (E_s) was determined using formula 1, while in the case of capacitors, formula 2 was used.

$$E_s = \frac{U \cdot I \cdot t}{m} \quad (1)$$

$$E_s = \frac{1}{2} C_s U^2 \quad (2)$$

Table 1. Key parameters for obtained systems

Parameter	CuO	SnS	CoS_2	Capacitor
E_s (Wh/kg)	356	613	809	10.3

The proposed battery configurations exhibit comparable manufacturing costs, attributable to the assumed availability of the specified materials [17]. The presented results indicate that a CoS_2 battery is the most suitable option for a single-track vehicle, offering the highest specific energy (gravimetric energy density) of 809 Wh/kg. To provide better insight into the achieved performance, the obtained capacitance results were compared with recent data reported for analogous systems employing different synthesis routes (Table 2). The vehicles under consideration are compact, which is among their principal advantages; consequently, the propulsion systems cannot be substantially enlarged without compromising functionality. It is therefore reasonable to employ an auxiliary battery module weighing 5 kg, which can be accommodated in the cargo space or integrated into the vehicle body. According to the literature survey, such a battery would enable a driving range of approximately 150 km, which is sufficient for the daily operation of an urban moped.

Table 2. Comparison of specific capacity and capacitance values obtained in this work with data reported in the recent literature for analogous electrolytes

System	Capacity	Literature value	Reference
CuO / Na-ion	164 mAh/g	525 mAh/g	[21]
SnS / Na-ion	295 mAh/g	839 mAh/g	[13]
CoS_2 / Na-ion	867 mAh/g	861 mAh/g	[25]
Lignin-based capacitor	63 F/g	311 F/g	[12]

Although the obtained capacities are slightly lower than the top-reported values in the literature, they were achieved using significantly simplified and environmentally friendly synthesis routes that did not require high-temperature activation, template-assisted methods, or multi-step pyrolysis. In particular, the CoS_2-based electrode exhibits a specific capacity higher than that of the optimized composite systems, while being much easier to fabricate and scale up.

The CuO- and SnS-based electrodes also exhibit stable electrochemical behavior with capacities suitable for practical sodium-ion applications, underscoring the effectiveness of the proposed preparation process. The lignin-derived carbon electrode shows promising capacitive performance in alkaline electrolyte, which can be further enhanced through structural optimization, confirming its potential as a sustainable alternative to conventional carbon materials.

6. Conclusions

Urban scooters are gaining prominence within the European Union's transport systems, and their electrification is a key element of sustainable mobility. Given the current constraints on the supply of rare earth metals, particularly lithium, exploring alternative battery chemistries is imperative. This study has demonstrated that environmentally friendly and simplified fabrication methods can yield high-performance electrochemical materials suitable for light electric vehicle applications. The investigated sulphide-based systems (SnS and CoS_2) and the novel eco-friendly LBG binder exhibited high initial specific capacities and satisfactory cycling stability, confirming their strong potential as anode materials for Na-ion batteries with good reversibility of intercalation–deintercalation processes.

The CuO oxide material demonstrated comparable electrochemical activity, supporting its role as a stable and efficient conversion-type electrode in sodium-ion systems.

The bio-based capacitor prepared using lignin-derived carbon exhibited excellent cyclic stability and reversibility, demonstrating that renewable materials can effectively replace conventional electrodes and marking a significant step toward sustainable energy storage technologies.

Among the evaluated solutions, the CoS_2-based battery is identified as the most advantageous, owing to its favorable energy-to-mass ratio and comparable production cost. A 5 kg module is estimated to provide a range of approximately 150 km per charge, which is sufficient for daily urban use. Moreover, the proposed materials exhibit favorable recyclability characteristics. Future work will focus on developing physical prototypes and integrating them with an L1e-B category urban two-wheeler propulsion system.

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