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Review about the Applications of Nanoparticles in Batteries

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ABSTRACT

Nanoparticles are defined as an organic or non-organic structure of matter in at least one of its dimensions less than 100 nm. Nanoparticles proved their effectiveness in different fields because of their unique physicochemical properties. Using nanoparticles in the power field contributes to cleaning and decreasing environmental pollution, which means it is an environmentally friendly material. It could be used in many different parts of batteries, including an anode, cathode, and electrolyte. This study reviews different types of nanoparticles used in Lithium-ion batteries by collecting the advanced techniques for applying nanotechnology in batteries. In addition, this review presents an idea about the advantages and disadvantages of using nanoparticles in batteries to harness energy without harming the environment. This review showed that applying nanotechnology and using nanoparticles in the production technique of batteries open the field for developing energy storage in Nano sized batteries. This, in turn, is important in the new era of technology in the industries of electronic devices and precision electrical appliances such as mobile phones, digital cameras, etc.

Keywords: Nanoparticle, Batteries, Anode, Cathode, and Electrolyte.

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مراجعة حول تطبيقات الجسيمات النانوية في البطاريات

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الخلاصة

تعرف الجسيمات النانوية على أنها بنية عضوية أو غير عضوية للمادة، يكون أحد أبعادها على الأقل أصغر من 100 نانومتر. أثبتت الجسيمات النانوية فعاليتها في مجالات مختلفة بسبب خصائصها الفيزيائية والكيميائية الفريدة. يساهم استخدام الجسيمات النانوية في مجال الطاقة في التنظيف وتقليل التلوث في البيئة مما يعني أنها مادة صديقة للبيئة. يمكن استخدامه في أجزاء مختلفة من البطاريات، بما في ذلك الآنود والكاثود والإلكتروليت. تقدم هذه المراجعة فكرة عن مزايا وعيوب استخدام الجسيمات النانوية في البطاريات لتسخير الطاقة دون الإضرار بالبيئة. وبدا واضحا أن تطبيق تكنولوجيا النانو واستخدام الجسيمات النانوية في تقنية إنتاج البطاريات يفتح المجال لتطوير تخزين الطاقة في البطاريات النانوية. وهذا بدوره مهم في العصر الجديد للتكنولوجيا في صناعات الأجهزة الإلكترونية والأدوات الكهربائية الدقيقة مثل الهواتف المحمولة والكاميرا الرقمية وما إلى ذلك.

الكلمات الرئيسية: الجسيمات النانوية، البطاريات، آنود، كاثود، المحلول الالكتروليتي.

1. INTRODUCTION

Batteries are the most noticeable applications in the energy storage field **(Manaktala and Singh, 2016**). They store electric power in the shape of chemical power. All batteries paintings at the equal principle. They are made from electrodes linked to a circuit. The effective electrode (cathode) is the electrode that takes up electrons while the battery is attached to a load. The terrible electrode (anode) is the electrode that offers off electrons as it is in operation. A chemical response at the anode creates electrons simultaneously, as the chemical response at the cathode uses electrons. The reactions create an electrical current. Some types of batteries could be recharged by reversing the electric circuit, wherein an externally implemented charge forces the electrons in the contrary direction **(Wolfgang et al., 2014).** Nanotechnology can dramatically affect battery production fields by enhancing the overall performance and satisfying substance requirements **(Thornton et al., 2004)**.

Nanotechnology is an essential branch of science that involves manipulating and creating nanometer-scale materials. Nanomaterials refer to materials in which at least one of the dimensions of the atoms or molecules is less than 100 nm in size. Where each nanometer (nm) equals 10^{-9} meters. Nanoparticles could be classified according to their dimension, morphology, composition, uniformity, and agglomeration **(Chokkareddy and Redhi, 2018)**. Furthermore, it could be classified mainly into organic and non-organic substances. Nanoparticles proved their effectiveness in different fields because of their unique physicochemical properties. As a result, nanotechnology promises to be a valuable tool to solve our problems and provide needed assistance in various applications. The design and development of new and innovative material properties at the nanoscale will enable new applications and solutions. When the size of the bulk materials is reduced to the nanometer sizes, the quantum mechanical properties of electrons contribute to their behavior as they dominate the physical properties. Electrons are confined in all three dimensions. The quantum mechanical properties of electrons contribute to their behavior and dominate the physical properties of electrons confined in all three dimensions.

Using nanoparticles in a battery increases the contact area between the electrode and the electrolyte. This is important since electrolytes will prevent ions from conducting ions. Nanoparticles provide penetration length and stress modulation, producing high power and capacity. Different types of nanoparticles could be used in batteries, such as Nano carbons, graphene, carbon nanotubes, etc. **(Kianfar et al., 2020)**. It is important to use inexpensive, low-conductivity nanoparticles in battery electrodes, such as lithium iron phosphate and lithium titanate. This resulted in commercializing batteries with those substances **(Cheng et al., 2011)**. Batteries are used in cellular packages, mobiles, laptops, computers, etc.

Using NPs in batteries opens up a wide area of research for researchers, increasing the efficiency, weight reduction, and life expectancy of this type of battery **(Jawad et al., 2016).** Nanoparticles may be exploited to enhance the electrochemical systems. It could be used in lithium batteries in two general groups:

1- Enhancing the overall performance of battery constituents such as anode and cathode.

2- Creating a variety of batteries, including flexible batteries, Nano-batteries, and 3D batteries.

Inert Nanomaterials could be used to improve conductivity. It was found that nanoparticles can provide high capacity and power by providing penetration length and stress regulation. Furthermore, it is a safe, stable, and low-cost substance.

(Giuriatti, 2018) modified a new battery by preparing two Nanofluids (NFs), one for the anode and the other for the cathode, by dispersion of two types of electroactive NP in the liquid base fluid. These NP include pristine (LMNO) and surface-modified TiO_2. The result shows that using TiO_2 gives a 58% better current than that of the pristine, with identical power spent for mixing. This, in turn, confirms that the surface remedy will increase the overall performance of NFs. **(Ye et al., 2014)** predicted a new method of preparing Si NPs intercalated in graphene sheets. The porous Si/G composite structure permits unfastened enlargement and contraction of Si NPs during decomposition and disassembly with no mechanical stress or constraints. Silicon is a metalloid and semiconductor material. It is less electron conductive than graphite **(Meng et al., 2021)**.

(Sun and Ni, 2022) prepared NiP and NiP@C substances utilizing solvothermal synthesis mixed with thermal decomposition, as shown in **Fig. 1 a and b,** respectively. They found that the NiP@C anode could deliver a reversible capacity of 385.5 mAh/g at 50 mA/g and maintained at 292 mAh/g after one hundred cycles. This led to a growth in the capacity retention of the NiP material from 21% to 75%. The results show that the diffusion rate of Na+ in NiP@C is faster due to the better electronic/ionic conductivity of carbon, which helps to improve the capability rate and cycling reversibility of NiP@C.

(Cui et al., 2022) prepared CoSe/C-NS nanocubes as shown in **Fig. 2.** In comparison with CoSe/C-N, CoSe/C-NS samples have the benefits of specific capabilities of low N and S-co-carbon shape and long-time period cycle stability that is beneficial in accelerating the electronic operation at high currents. The CoSe/C-NS anode material delivers a high specific capacity of 1494 mAh/g after 300 cycles at a current density of 2 A/g.

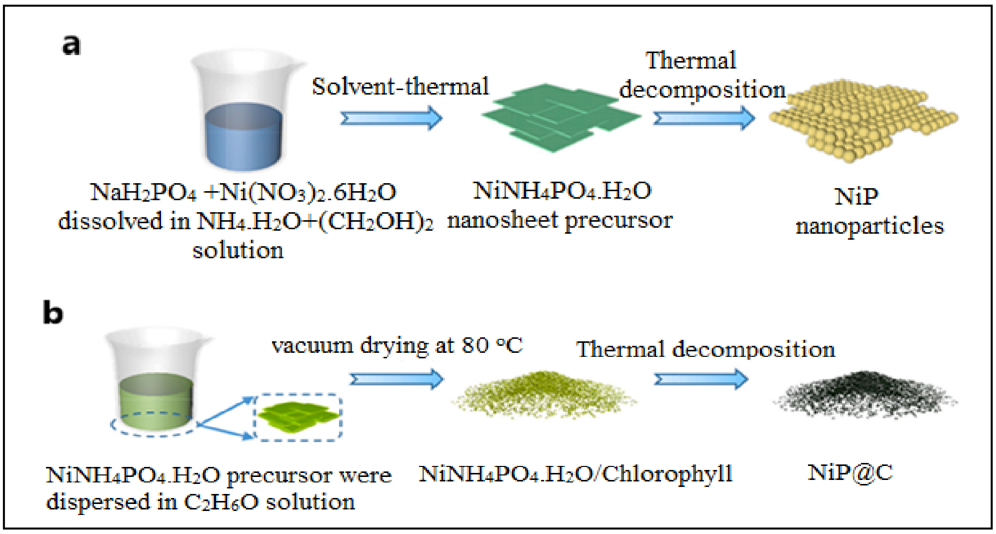

Figure 1. Preparation steps of (a) NiP and (b) NiP@C **(Sun and Ni, 2022)**

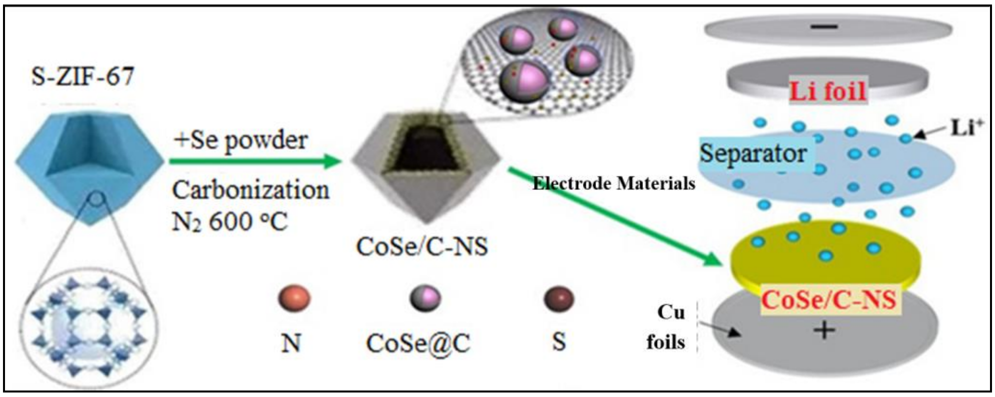

Figure 2. N/S co-doped CoSe/C nanocubes in LIB **(Cui et al., 2022)**

(Wu et al., 2022) arranged a silicon carbon hybrid Si@3DC by anchoring silicon NPs on the third-dimensional carbon structure as appeared in Fig.3. Carbon thin layer on the surface of silicon NPs encourages the creation of a firm solid electrolyte interphase. That's, in turn, important to ensure excellent overall cycle stability performance of Si@3DC reaching 1,588 mAh/g and ability retention of 74.8% at 2 A/g after 1,000 cycles.

(Yi et al., 2016) suggested synthesizing Sb/C composites systematically beginning from ZIF-sixty-seven. **(Wang et al., 2018)** suggested a way in which a chemical course is used to gain the antimony NPs' internal porous carbon structures. **(Zhang et al., 2018b)** explored the performance of using (Sb) nanoparticle-embedded carbon Nano sheets Sb@C and LiFePO4/C Nano sheets within the battery. The result shows incredible stabilities, referring to the realistic utilization of these Nanosheets in LIBs.

(Chen et al., 2022) used the hydrothermal method to synthesize the Si/s-C@TiO_2 hybrid to ensure the embedding of Si-NPs in round carbon and the coating of the TiO_2 shell. The result showed excessive balance and excessive-overall performance anode substances for LIBs. Furthermore, this method improved the ionic conductivity of the hybrid. The electrochemical measurements confirmed that using Si/s-C@TiO_2 hybrid in battery produces an overall performance of 780 mAh/g with a coulombi performance of ninety-nine percent after one hundred cycles.

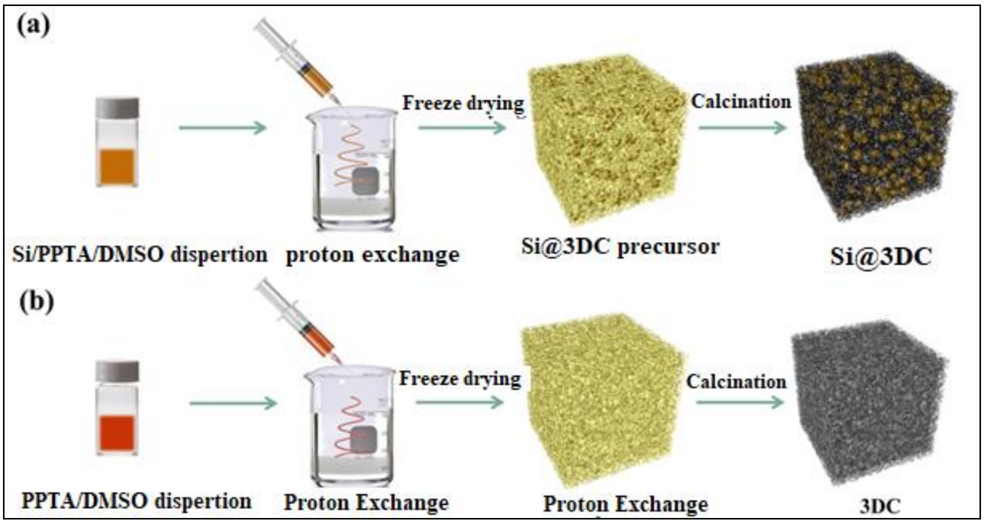

Figure 3. The preparation process of (a) Si@3DC and (b) 3DC **(Wu et al., 2022).**

(Luo et al., 2021) studied the dispersing of silver NPs in 1 M lithium perchlorate/dimethyl sulfoxide electrolyte of lithium/oxygen battery experimentally. The result appeared to improve the conductivity. Another experimental and theoretical research implied that dispersing silver NPs can absorb soluble O_2, which is liable to remedy oxidative cleavage of electrolytes and corrosion of lithium anode. This, in turn, dramatically increases lithium-oxygen batteries' lifespan from 55 to 390 cycles.

Carbon nanotubes (CNTs) are featured by their mechanical and electric properties and advanced construction blocks that could be used as specific additives in bendy batteries **(Zhu et al., 2021)**. **(Hwang et al., 2022)** used carbon coating technique using phenolic resin to solve the volume enlargement problem of silicon anodes. This, in turn, improved the performance of LIBs resulting in an excessive unique potential of the overall performance of the carbon-silicon anode reaching 3092 mAh/g and high capacity retention of about (100 after 50 cycles) and (64 after 100 cycles) at 0.05 ^{o}C.

(Zhu et al., 2018) synthesized super-aligned CNT arrays through a low-strain chemical vapor deposition method (CVD). A thin-film LIB was assembled using the loose status TiO_2/CNT anode and $LiMn_2O_4$/CNT cathode. The result appeared no apparent overall performance degradation after 500 bending cycles. **(Liu et al., 2018)** fabricated horizontally orientated CNT films of (1800 mm×1000 mm) size and used them in excessive foldable thin-film LIBs. The result appeared to have better electric conductivity and an extreme capacity of 700 mAh.

(Gu, 2021) studied the development strategies of three materials, silicon, lithium titanate, and transition steel oxides, to use them in anode materials. These strategies are based totally on nanotechnology, its advantages and disadvantages, and the progress of modern-day studies. **(Jawad et al., 2016)** summarizes battery material technologies that are being developed by adding NPs, increasing the efficiency of lithium-ion batteries. **(Kianfar et al., 2020)** described the application of nanotechnology in LIBs, which can be generalized to other batteries such as sodium-ion and magnesium-ion. They discuss the benefits of nanofabrication to increase power output and capacity. They also describe the drawbacks, such as reduced volumetric energy density. Generally, synthesizing NPs and modifying nanoscale electrodes are important in this age. They mentioned the software of nanotechnology in lithium-ion batteries which can be applied in a general manner for different types of batteries using magnesium and sodium ions **(Kianfar et al., 2020)**. Graphite is currently the maximum used anode material since it has excellent stabilities and slight particular capacitance with a theoretical capacity of 372 mAh **(Asenbauer et al., 2020).**

(Heo et al., 2020) studied the effect of using NPs in the raw materials of LiMn2O4 cathode with organic–inorganic hybrid electrolytes of bending batteries using pyro-synthesis. The results showed that the free capacities for the micro- and Nano-LMO substances were 118.41 and 138.12 mAh/g, while the columbic efficiencies were 91.50% and 97.28%, the discharge capacities were 85.63 and 99.96 mAh/g, and the coulomb efficiencies were 79.27% and 90.27% respectively. That results from the nanoscale sizes of $LiMn_2O_4$, the short diffusion paths, and the large contact area at the electrode/electrolyte interface.

(Li et al., 2022) prepared battery electrodes using CoS_2@rGO (CSG) nanocomposite (which was synthesized using the hydrothermal method) and tested for charge-discharge performance. The results indicate that CSG nanocomposites have high reversible specific capacity, excellent rate performance, and superior cycle performance when used in the negative electrode of LIBs. The prepared battery showed that the specific capacity retention after 100 cycles was 61.5%, 47.5% higher than that of pure CoS_2 nanomaterial **(Li et al., 2022).**

Reduced graphene oxide (rGO) distinguishes by the simplicity of preparation, the extraordinarily thin interfacial distance of 0.36 nm, huge surface area, excessive conductivity, and high chemical firmness. These advantages made rGO used largely as an auxiliary material in LIBs **(Xie et al., 2019).** Furthermore, rGO assists in preventing the inorganic NPs from aggregate and agglomerate processes.

It is found that minimizing the metallic sulfide debris to the nanoscale cause increasing in the material-specific surface area and shortening the ion diffusion path, decreasing the material's size effect **(Galushkin et al., 2020).** Wang and his coworkers first prepared CoS_2/C composites using a self-established template technique. The result appeared that the reversible capacity of CoS_2 became approximately 700 mAh/g for the first time, and the specific capacity became 560 mAh/g after 50 cycles **(Su et al., 2014).**

Both CNTs and carbon nanofibers contain an open mesoporous, allowing ions to transfer to the interface of the double layer. Several examples have been suggested and found that the capacitance of CNT exceeds that corresponding to traditional activated carbons only if these are functionalized by oxidizing their surface or adding some impurities **(Obreja, 2008)**. Another example includes using carbon aerogels and fullerene-like carbon NPs to enhance the capacitance, resulting from low electronic charging and ionic resistance **(Wang et al., 2001).** Using Nano-templates such as mesoporous silica, zeolites, etc., to synthesize CNT has been investigated for carbon electrodes. CNT combines the high specific surface area and the electrical conductivity without using additives such as binding materials to enhance the mechanical strength or conductive additives. **(García-Martínez et al., 2008)** found that the morphology greatly affects the rate capability and the storage of vanadium pentoxide (V_2O_5). They proved that the performance of core–shell Nano cable is better than that of Nanorods or nanotubes. CNT could be significant in electrochemical systems since using SWCNT electrodes improved the performance of batteries **(Terrones, 2003)** and fuel cells **(Girishkumar et al., 2005)**.

This study aims to provide an idea of the possibility of using various types of nanoparticles in the internal composition of Lithium-ion batteries to highlight the advantages of using them economically and environmentally globally.

2. MATERIALS OF SOME TYPES OF BATTERIES

Batteries could be made of different metallic ions, such as Lithium-ion batteries (LIBs), Sodium-ion batteries (NaBs), and Zinc-ion batteries (ZnBs) **(Yasin et al., 2020)**. Among these batteries, Lithium-ion batteries (LIB) appeared as a turning factor in 1991, features to their long cycle life, high voltage, and excessive electric density **Fig. 4** presents a schematic diagram illustrating a LIB.

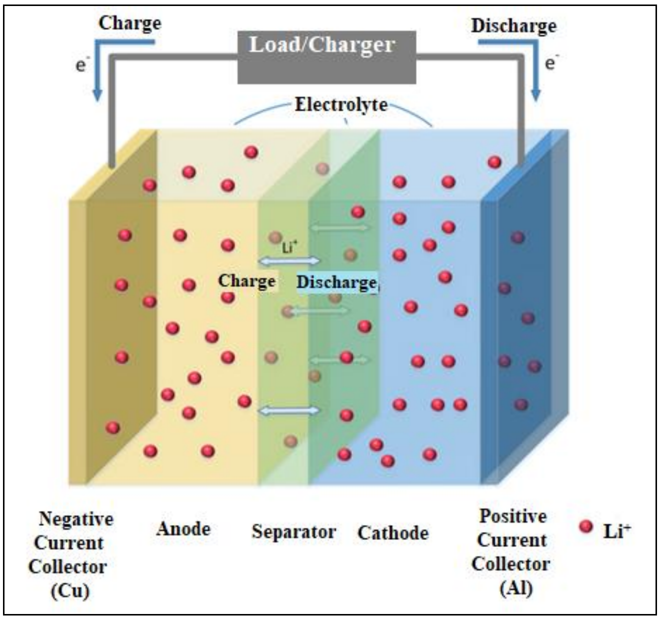

Figure 4. A schematic diagram illustrates a LIB **(Zhang et al., 2018a).**

Using sulfide anodes instead of oxides in lithium-ion batteries attracted great interest because of their high capacity, decreased electro-negativity, and higher performance. In addition, the morphology of sulfide anodes is simple and can be controlled and modified to have higher capacity than other anode materials **(Fei et al., 2013; Schanze and Mallett, 2016).** Despite using sulfide as a lithium-ion electrode material has the disadvantages of low conductivity and low cycle stability **(Tu et al., 2021)**, cobalt sulfide is an attractive candidate for the anode of LIBs because of its unique chemical and physical properties **(Li et al., 2022)**. Lithium-metal in LIBs can react easily with air and water and has a low melting factor. As a result, it changed by using different stable substances, such as carbon which is used as a slurry-covered layer **(Torabi, 2011).**

Furthermore, Silicon has a completely excessive specific capability for LIBs anodes of about 3579 mAh/g based totally on the Li15Si4 formation, offers an excellent theoretical capacity of the anode exceeding ten times that of graphite, reaching about 100%–200% **(Zhao and Lehto, 2021). (Hamza et al., 2016)** synthesized ZnO Nano-powder using hydrothermal methods. The study showed that the electrical conductivity increased with the amount of nanoparticles. The anodes of some types of batteries are manufactured from graphite; each unit contains graphite with six carbon atoms. The theoretical ability reached 372 mAh/g. Theoretically, one lithium atom can react with one tin atom to shape Li4.4Sn alloy. The ability of the tin anode comes to 993 mAh/g, which is three instances that of graphite. However, introducing a large amount of Li with Sn can lead to a size tolerance (about

300%), causing the crushing of small particles and thus reducing the electrochemical performance **(Xu et al., 2013).**

Unique nanoscale particle physics must be prepared and investigated to improve battery performance using the nanoscience technique. For example, **(Xu et al., 2006)** compared the electrochemical behavior of Fe_2O_3 nanoscale with microscale samples of the same material. Furthermore, they made electrochemically active Li_2MnO_3 using electrochemically inactive by developing nanostructured material. Many researchers have searched for suitable anode substances for LIB to enhance their electricity densities. They discovered that nanostructured Nickel oxide electrodes (NiO) featured their high capacity, low cost, and porous structure, allowing electrolyte penetration and providing a massive electrode–electrolyte touch area. In addition, NiO can integrate with conductive matrixes with carbon, graphene, conducting polymers, and metals. It's discovered that 3D porous nanoscale Ni/NiO composite with hydrogen-bubble template-assisted chemical deposition and electro-deposition techniques had proven hierarchical porosity and excellent electrochemical performances for LIB **(Bello et al., 2013; Manidurai and Sekar, 2017).**

3. NPS REDUCING CHARGE TIME FOR MOBILE

Using NPs in batteries can enhance mobile batteries' charging and discharging time, which could be reduced to seconds or minutes depending on storage capacity. Nano matrix composites could be used in electrical transport technology and mobiles as energy storage units. Nanocomposites may minimize the misuse of energy in the energy sector by improving the features of electrical cables. In addition, polymer electrical conducting could be enhanced by using NPs and conducting ions **(Manaktala and Singh, 2016)**.

Using NPs in the material of mobile battery could increase the interfacial surface area between the electrolyte and the electrode that results from the high surface/volume ratio of NPs. This, in turn, makes them more reactive. On the other hand, this cause increased unwanted reactions between the electrode and the electrolyte, which could be solved using nanotechnology by reducing the required penetration length and increasing the battery power. Battery energy could be improved using NPs. That appears clearly in the following equation: $D = L2/t$, which is the characteristic time. L is the particle length, and D is the diffusion coefficient. D is almost constant. Thus decreasing the dimension represented by L will cause reducing the penetration time twice. For example, in $LiFePO_4$ battery, using a particle length of 2 microns made the penetration time 83 hours, while using a particle length of 40 nm caused a typical time reduction to 13 seconds **(Lee et al., 2002; Kim et al., 2005; Malini et al., 2009; Scrosati and Garche, 2010; Tiwari et al., 2012).**

4. THE ADVANTAGES AND DISADVANTAGES OF NPS IN BATTERIES

The benefits of using NPs in batteries could be summarized as follows:

1) Fast charging and discharging, quick reactions, and immediate ions transfer **(Goutam et al., 2017)** due to the large interface surface area between the electrolyte and the electrode **(Kianfar et al., 2018a)**.

2) Reducing the time required for lithium ions and electrons to enter the electrode. This, in turn, results in higher power and capacity **(Kianfar et al., 2018b).**

3) Enhancing batteries' performance and increasing their cycle life by reducing mechanical failure since the volume change of active material that results from lithium ions

entering and leaving the electrolyte during the chemical reaction between the electrodes is easy (**Kianfar, 2019; Bhatnagar et al., 2022**).
4) Reduction in inert electrode materials' use results in improved electrode capacities **(Kianfar and Salimi, 2020)**.
On the other hand, the disadvantage of using NPs in batteries is that their expensive prices prevent their use in the large batteries industry. As a result, they can be useful and economical for micro-batteries where the NPs price is not an important factor.
Fortunately, in the present time, many researchers have studied the possibility of producing a low-priced, conductive, and excessive aspect ratio nanomaterial to be used in batteries of different sizes.

5. CONCLUSIONS

In conclusion, using nanotechnology in battery production has large advantages. For example, it can lessen the price of electricity production, distribution, and storage by decreasing the number of substances used without compromising the predicted electricity outputs. As a result, it could be important in the power field. It could be used in supplying power to the national grid. Using NPs in batteries reduces the transfer distance between the electrons and ions, and additionally, NPs can slow down the duration of the charging and discharging process. Using NPs in batteries can make mobile battery charging and discharging time in seconds or minutes, depending on storage capacity. Furthermore, Nanotechnology is environmentally friendly since it could contribute to cleaning and decreasing the environmental effect in the power field.

NOMENCLATURE

Symbol	Description	Symbol	Description
C	Carbon	nm	nanometer
CNTs	Carbon nanotubes	NPs	nanoparticles
CVD	chemical vapor deposition	PbO	Lead oxide
D	Diffusion coefficient.	rGO	Reduced graphene oxide
L	particle length	SnO_2	Tin oxide
LIBs	Lithium-ion batteries	SWCNT	Single-Walled Carbon Nanotubes
mAh	milli Amper hour	t	time
NaBs	Sodium-ion battery	V_2O_5	vanadium pentoxide
NFs	Nanofluids	Zn	Zinc
NiO	Nickel oxide electrodes		

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