Sustainable regeneration of cathode active materials from spent lithium-ion batteries by repurposing waste coffee powder

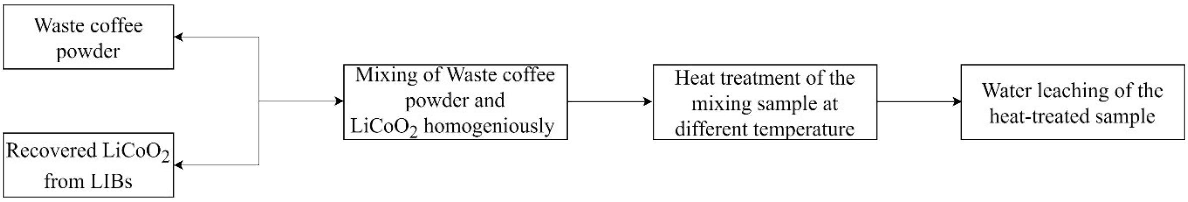

Figure S1: The experimental setup diagram of coffee powder reduction

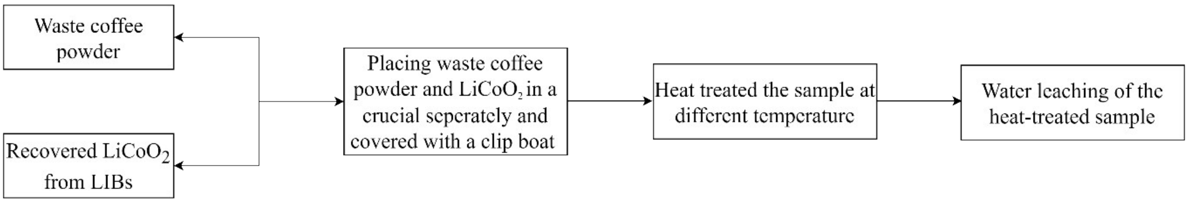

Figure S2: The experimental setup diagram of gas reduction

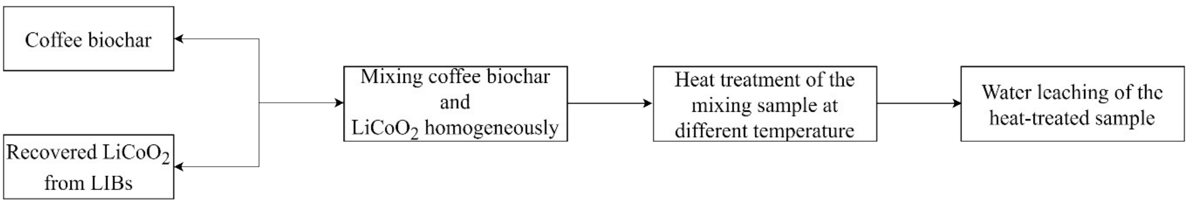

Figure S3: The experimental setup diagram of biochar reduction

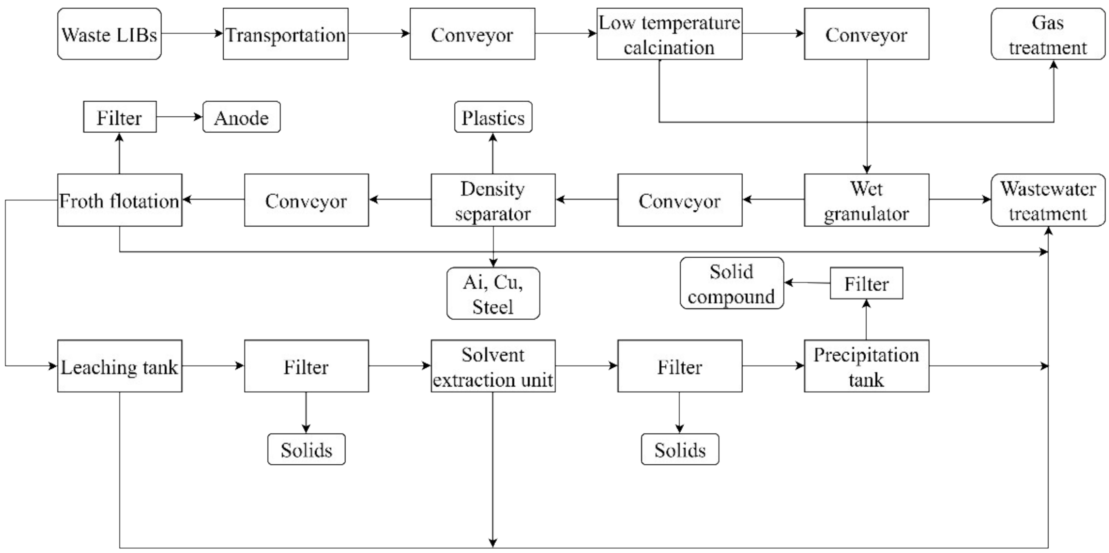

Figure S4: Hydrometallurgy process applied in EverBatt closed-loop battery recycling model

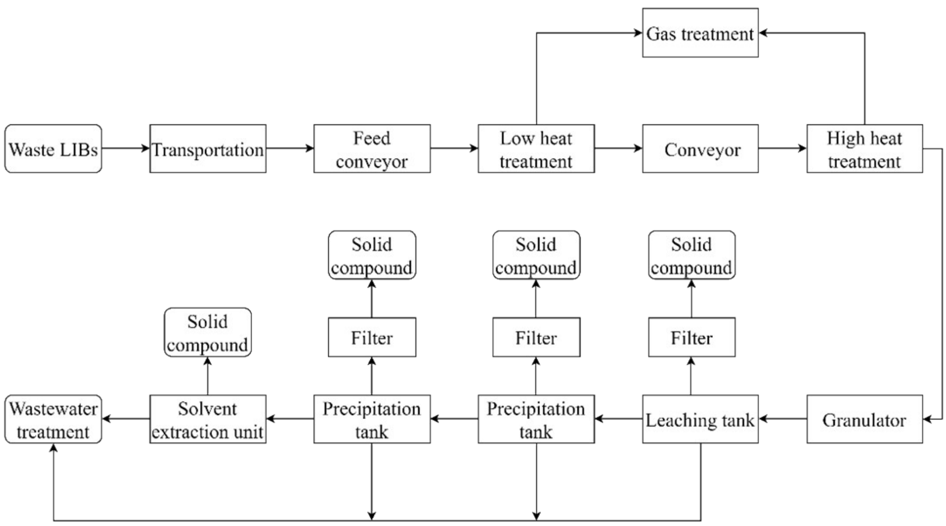

Figure S5: Pyrometallurgy process applied in EverBatt closed-loop battery recycling model

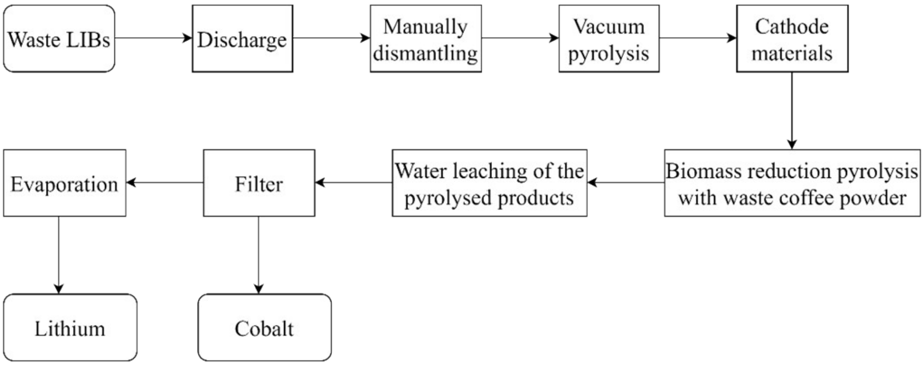

Figure S6. Direct recycling process of spent LIBs used in this study

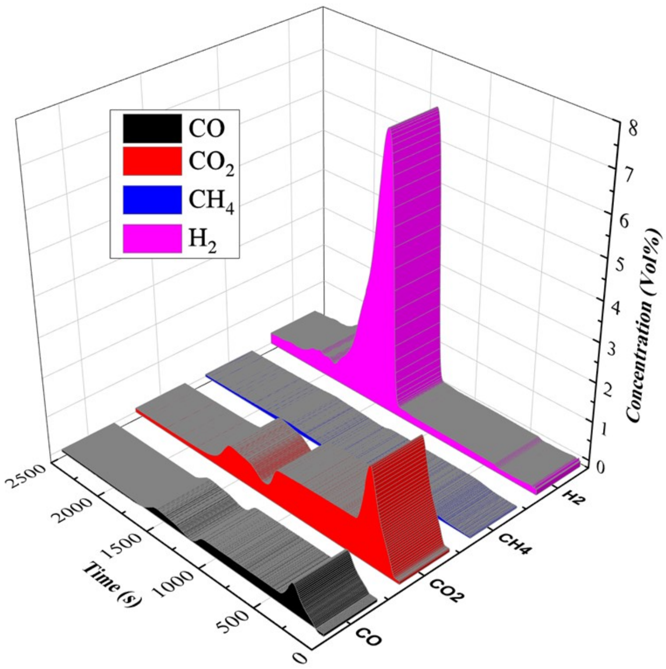

Figure S7: Gas generation from the coffee powder at 600°C

Table S1: The elemental analysis of Li_2CO_3 and Co/CoO

Element	Unit	Sample	
		Li_2CO_3	Co/CoO
Li	mg/g	166.034	0.008
Co	mg/g	0.004	149.753
Si	mg/g	0.089	0.937
Na	mg/g	0.005	0.003

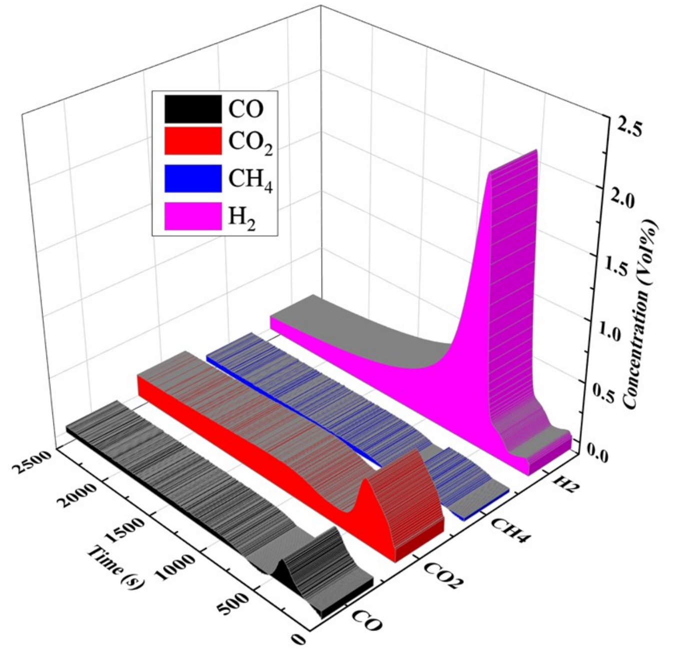

Figure S8: Gas generation from biochar reduction at 600°C

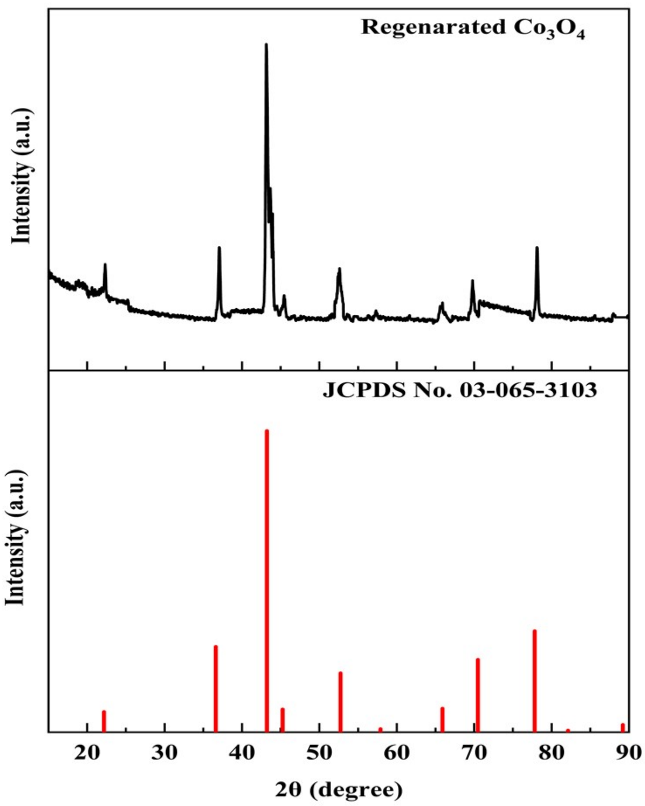

Figure S9: XRD pattern of the regenerated Co_3O_4

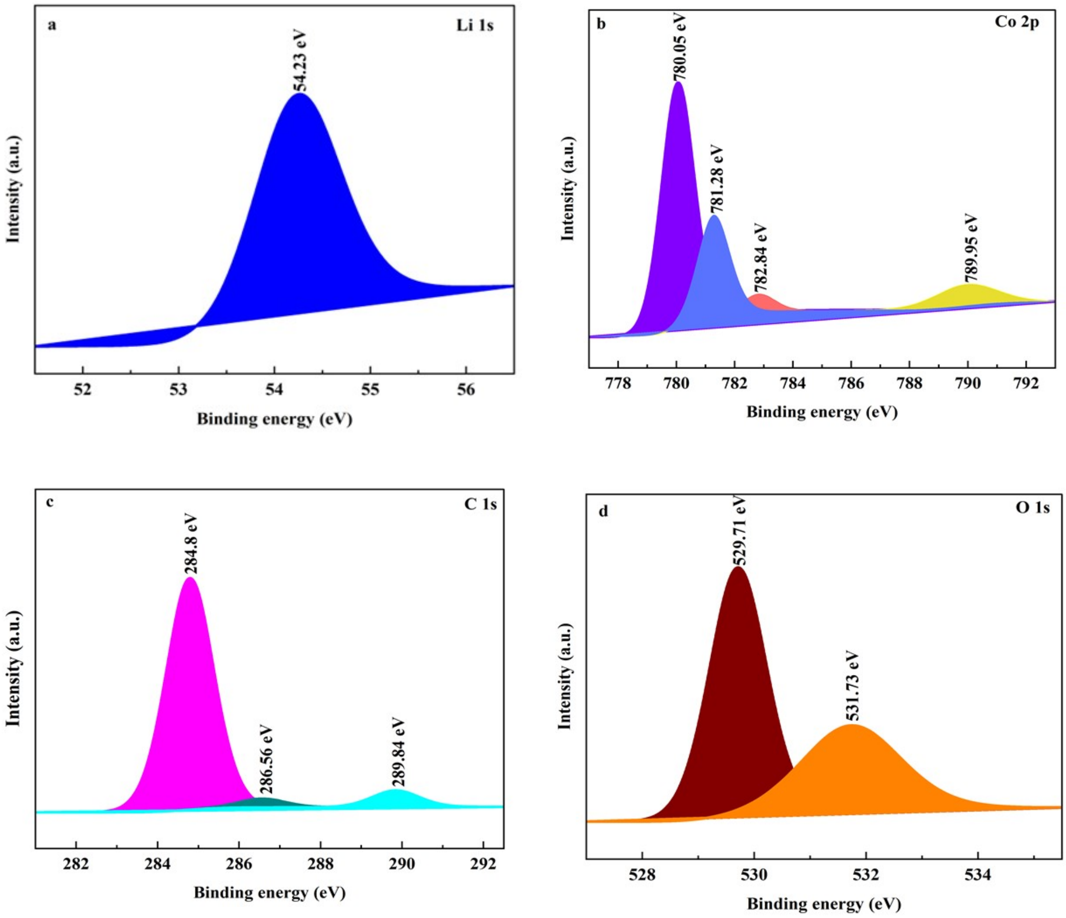

Figure S10: XPS spectra of regenerated $LiCoO_2$

4. Impact on Sustainable Development Goals

In 2015 the United Nations developed 17 sustainable development goals (SDG) as a universal call to protect the planet and end poverty by 2030 so that all people can enjoy prosperity and peace (Anastas et al., 2021). The present study of recycling of LIBs by utilizing waste coffee biomass falls under SDG 7 (Ensuring sustainable, reliable, and affordable energy for all), SDG 8 (Promoting sustainable economic growth), SDG 9 (Promoting sustainable innovation and industrialization), SDG 11 (Sustainable cities and comminates), SDG 12 (Sustainable consumption and production), SDG 13 (Climate action), and SDG 15 (Life on land) (figure 19). Here is some discussion of how those SDGs are related to our study.

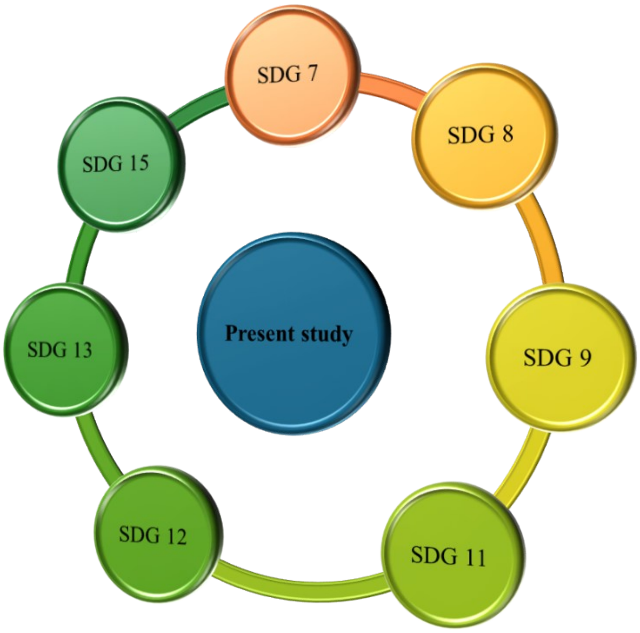

Figure S8: The number of sustainable development goals related to the present study

SDG 7- Ensuring sustainable, reliable, and affordable energy for all

Deficiency in transformation systems and energy supplies is one of the main obstacles to economic and human development. However, nowadays LIBs are extensively used in power grid storage systems, electric vehicles, and different consumer electronic products because of their unique advantages such as low discharge rate, no memory effects, and high energy density (Du et al., 2022). However, with the increasing demand for LIBs, the sources of raw materials for the manufacturing of LIBs are declining day by day. In our present study, we demonstrate a sustainable solution for the recovery of cathode material for the manufacturing of LIBs. In this study, we recovered lithium cobalt oxide which is one of the primary raw materials for the manufacturing of LIBs. We believe that if we can recover the lithium cobalt oxide from the waste LIBs, in the near future we can supply enough cathode material for the manufacturing of LIBs. Thus, the present study ensures sustainable, reliable, and affordable energy for all which is SDG 7.

SDG 8- Promote sustainable economic growth

With the advancement of the technology and economic development of society, the utilization of LIBs in different fields has increased significantly. From the year 2018 to 2019 the increased rate of electric vehicles throughout the world is around 64% and it is expected that by 2040 this rate will rise to around 80% (Baum et al., 2022). However, the world reserves of the primary raw materials for the manufacturing of LIBs such as cobalt and lithium are limited, and their mining process is laborious and energy-intensive (Farjana et al., 2019). In our study, we developed a sustainable and cost-effective way for the recovery of lithium cobalt oxide. From the "Analysis of environmental and economic aspect" section it has been observed that the present recovery method is far better than the other technology. The present recycling technique shows the lowest cost and highest revenue leading to earn profit of $23.62 from 1kg of cathode material. Again, our study not only reduces the recovery cost but also ecofriendly which promotes sustainable economic growth (SDG-8).

SDG 9 - Promote sustainable innovation and industrialization

For the betterment of the world sustainable innovation and industrialization are mandatory and without sustainable innovation the world will be a worse place to live in the future. The main parameter that plays a vital role in the industrial revolution is sustainable innovation. From the previous section (Analysis of environmental and economic aspects) discussion we have observed that in terms of lithium cobalt oxide recovery from the waste LIBs, our present study is more sustainable than the conventional technology. The application of the present study in the industrial sector not only gives economic benefits but also promotes a green environment. So, we can say that our study fosters sustainable innovation and industrialization (SDG 9).

SDG 11- Sustainable cities and communities

With the increasing of the population, the number of cities and communities is also increased but all the cities and communities are not safe enough to live in. The major inputs for a city or a community are food and energy in return outputs from a city or community are wastewater, solid waste, and air pollutants that not only the city or community but also the surrounding environment (Smith & Bricker, 2021). In SDG 11 there are 7 targets among them one is to provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety. Nowadays accessible, affordable, safe, and sustainable transport systems mostly rely on the LIBs. However, in the conversion of modern cities and communities, LIBs are playing a vital role in both the energy and transportation sectors. In our study, we not only recovered valuable materials from waste LIBs but also played a vital role in the supply of raw materials for the manufacturing of new LIBs. With the management of waste LIBs and the production of new LIBs from the recovered materials, the outcome of this study ensures sustainable cities and communities.

SDG 12-Sustainable consumption and production

According to the UN sustainable consumption and production refers to the use of services of the products in such a way that can fulfill the basic needs and reduce the emission of pollutants during production, service period as well as after the end of the service life (Team, 2023). In our study, we used the two most potential solid wastes: one is waste coffee powder, and another is waste LIBs. We not only developed a way to manage solid waste but also found another way to utilize it after the end of the service life. By incorporating our technology on the one hand we sustainably consume the waste materials and form the other hand by utilizing those waste materials we sustainably produce valuable materials for our society. So, our study fulfills the requirements of SDG 12-Sustainable Consumption and Production.

SDG 13-Climate action

Recycling both waste LIBs and coffee powder helps to reduce carbon emissions. From our study, we have observed that waste coffee powder-assisted LIBs recycling also reduces greenhouse gas emissions. The greenhouse emission from the conventional hydrometallurgy and pyrometallurgy recycling of waste LIBs is 1.93 and 2.41 kg/kg cathode cell respectively. On the other hand, waste coffee powder incorporated LIBs recycling shows greenhouse emissions of only 1.12 kg/kg cathode cell. Therefore, we can say that the present study contributes to SDG 13.

SDG 15-Life on land

The average life span of the LIBs which are used in small devices such as computers, laptops, and mobile phones is only 2-3 years whereas when they are used in large equipment such as electric vehicles (EVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), the average life span is bit longer 5-10 years (Chen et al., 2019). The skyrocketing usage and short life spans meant that every year more LIBs would be thrown away and became solid waste. The spent LIBs contain hazardous substances such as different heavy metals and electrolytes and if it is not managed properly, they will create several environmental pollutions that will affect all the life on the land (Zheng et al., 2024). On the other hand, every year around fifteen million tonnes of waste coffee powder are discarded in the landfill, from which a high amount of greenhouse gas is emitted that directly or indirectly affects the life on the land. In our study, we used waste coffee powder as a source of biomass and recovered valuable metals from the spent LIBs. So, our study paves the way for the management of the two most significant solid wastes, and that will give some comfort in the life present on the land.

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