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Journal of Scientific Reports-C dergisi, yayın hayatına 2000 yılında başlayan Dumlupınar Üniversitesi Fen Bilimleri Enstitüsü Dergisinden ayrılmış olup, Nisan, Ağustos ve Aralık aylarında olmak üzere yılda düzenli olarak 3 kez yayımlanan uluslararası hakemli bir dergidir. Derginin yazım dili Türkçe ve İngilizce'dir. Dergiye gönderilen makaleler, editör kurulu tarafından seçilen ve konusunda uzman en az iki hakem tarafından değerlendirilmektedir. Dergiye sunulan bütün makaleler çift-körleme yöntemiyle değerlendirilmektedir. Değerlendirilmek üzere dergimize gönderilen makalelerin, daha önce yayınlanmamış, yayınlanmak üzere kabul edilmemiş ve yayınlanmak için başka bir dergide değerlendirilme sürecinde olmaması gerekmektedir. Dergide yayınlanan yazıların her türlü sorumluluğu yazar(lar)ına aittir.

Dergi, fen ve mühendislik bilimlerinde ulusal ve uluslararası düzeyde yapılan bilimsel çalışmaları bilim insanları ve kamuoyu ile paylaşmayı amaçlar. Dergiye, fen ve mühendislik bilim dallarında yapılan, özgün araştırma makaleleri, derleme makaleleri ve kısa notlar kabul edilir. Özgün araştırma makalelerinin başka dergilerde yayınlanmamış olması, teorik ve deneysel sonuçlar içermesi beklenir. Derleme makalelerinde ise belirli bir konu üzerinde bilimsel, teknolojik ve güncel gelişmelerin geniş bir kaynakça kullanılarak yansıtılması ve bunların doyurucu bir değerlendirilmesinin yapılması aranır. Kısa notlar, özgün bir çalışmanın ilk bulgularının duyurulması amacına yönelik hazırlanan kısa yazılar olmalıdır.

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DERLEME MAKALE / REVIEW ARTICLE

A comparison of traditional and state-of-the-art machine learning algorithms for type 2 diabetes prediction

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Abstract

This research investigates the use of machine learning algorithms for early detection of diabetes. Due to its global prevalence and significant impact on health, timely identification of diabetes is crucial for effective treatment. In this study, machine learning models including Gradient Boosting Machines, Extreme Gradient Boosting, Light gradient-boosting machine, Categorical Boosting, k-Nearest Neighbors, Random Forest, Ridge Classifier, Logistic Regression, Gaussian Naive Bayes, and Decision Tree are utilized to assess their capabilities in diabetes diagnosis. The primary aim is to train these models to distinguish between individuals with diabetes and those without, using relevant features from the dataset. Since the classes in the dataset are imbalanced, the SMOTE technique is applied to improve model performance. Categorical Boosting achieved the highest accuracy rate of 90.05%, making it the most successful model. By systematically evaluating the performance of these prominent machine learning models, valuable insights can be gathered regarding their ability to recognize complex patterns indicative of diabetes. As a result, healthcare professionals and researchers can leverage this newfound understanding to develop more accurate and effective diagnostic tools, enabling early intervention and subsequently improving the overall quality of life for individuals affected by diabetes.

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1. Introduction

Diabetes is a chronic disease characterized by high blood glucose (sugar) levels. Glucose is a vital energy source for the body's cells, but it requires insulin, a hormone produced by the pancreas, to enter the cells. In people with diabetes, their body either does not produce enough insulin or cannot use it effectively, resulting in elevated blood glucose levels [1]. There are two main types of diabetes: Type I and Type II diabetes. Type I diabetes usually begins in childhood and adolescence. Patients must inject insulin externally. Type II diabetes occurs with advancing age. In the initial stages, it can be controlled with diet and exercise, but in advanced cases, medication or insulin injection may be required [2]. The cause of diabetes is not fully understood. However, there are several reasons of diabetes, including a person's lifestyle and genetics.

Diabetes necessitates constant medical care to lower the risk of several health concerns, including neuropathy, kidney failure, cardiovascular issues, and vision impairment [3]. Early identification and treatment are essential to avoiding the disease's secondary complications as well as any long-term effects.

Research has focused on using various classification techniques for diabetes prediction [5]. These studies aim to develop accurate and reliable models for early diagnosis and intervention. Xie et al. attempted to create risk prognosis models for Type 2 diabetes by applying the Synthetic Minority Oversampling Technique (SMOTE) to eliminate class imbalance in the BRFSS 2014 (Behavioral Risk Factor Surveillance System) dataset. With 82.4% accuracy, their results showed that the neural network offered the best overall accuracy rate among all models [5]. Wei and colleagues conducted a comprehensive analysis of diabetes detection approaches using the Pima Indian dataset, focusing on Deep Neural Networks and support Vector Machines (SVM) [6]. In another study, Yahyaoui et al. used the Pima Indian dataset to examine the performance of SVM, Random Forest (RF), and Convolutional Neural Network models for diabetes prediction. They found that RF was the most effective model, with an accuracy rate of 83.67% [7].

Our research seeks to obtain high accuracy rates, thoroughly evaluate different machine learning approaches for diabetes diagnosis, and assess the BRFSS 2015 dataset utilized for diabetes diagnosis. The aim is to identify which techniques are most suited for obtaining the most accurate and reliable outcomes in the diagnosis and prognosis of diabetes by contrasting the performance of different methods.

The introduction comprehensively introduced the overall objectives and methodology of the research. The following section provided information about the dataset used for diabetes diagnosis and discussed data preprocessing techniques in detail. Additionally, it explained machine learning models used for classification. Section 3 presented the experimental results of the machine learning models used in diabetes classification. The 4th and final section presented a summary of the findings, general conclusions, contributions of the study, and recommendations for future research.

2. Material and methods

2.1. Dataset

In this study, the data set named "Diabetes Health Indicators Data Set" obtained from Kaggle was used [8]. The dataset was derived from the BRFSS-2015 results, one of the most widespread and comprehensive public health surveys in the United States. Three CSV data sets were produced for diabetes prediction from BRFSS-2015 survey data. The dataset we use consists of 253,680 survey responses. The data set we use includes a total of 22 features such as diabetes status, high blood pressure, cholesterol, physical activity, smoking habit, gender, age, education level, income level, general health and mental health status. These features and their properties are shown in Figure 1. Investigating the importance of these features in diabetes prediction directly affects model performance.

Diabetes_binary: Indicates whether the respondent has diabetes (0: No, 1: Yes).

HighBP: Indicates if adults have been informed by a healthcare professional about having high blood pressure (0: No, 1: Yes).

HighChol: Indicates if the respondent has ever been informed by a healthcare professional that their blood cholesterol is high (0: No, 1: Yes).

CholCheck: Indicates if the respondent had a cholesterol check within the past five years (0: No, 1: Yes).

BMI: Body Mass Index (BMI).

Smoker: Indicates whether the respondent has smoked at least 100 cigarettes in their entire life (0: No, 1: Yes).

Stroke: Indicates if the respondent has ever been told by a healthcare professional that they had a stroke (0: No, 1: Yes).

HeartDiseaseorAttack: Indicates whether the respondent has ever reported having coronary heart disease (CHD) or myocardial infarction (MI) (0: No, 1: Yes).

PhysActivity: Indicates if the respondent reported doing physical activity or exercise during the past 30 days other than their regular job (0: No, 1: Yes).

Fruits: Indicates whether the respondent consumes fruit 1 or more times per day (0: No, 1: Yes).

Veggies: Indicates whether the respondent consumes vegetables 1 or more times per day (0: No, 1: Yes).

HvyAlcoholConsump: Indicates heavy drinkers, defined as adult men having more than 14 drinks per week and adult women having more than 7 drinks per week (0: No, 1: Yes).

AnyHealthcare: Indicates whether the respondent has any kind of health care coverage, including health insurance, prepaid plans, or government plans (0: No, 1: Yes).

NoDocbcCost: Indicates if there was a time in the past 12 months when the respondent needed to see a doctor but could not due to cost (0: No, 1: Yes).

GenHlth: Indicates the respondent's general health rating on a scale of 1 to 5.

MentHlth: Indicates the number of days during the past 30 days when the respondent's mental health was not good (0 to 30).

PhysHlth: Indicates the number of days during the past 30 days when the respondent's physical health was not good (0 to 30).

DiffWalk: Indicates if the respondent has serious difficulty walking or climbing stairs (0: No, 1: Yes).

Sex: Indicates the gender of the respondent (0: Female, 1: Male).

Age: Represents a fourteen-level age category (1 to 14).

Education: Indicates the highest grade or year of school the respondent completed (1 to 6).

Income: Represents the annual household income from all sources, coded from 1 to 8. If the respondent refuses at any income level, it is coded as "Refused."

Fig. 1. Dataset features.

The pie chart presented in Figure 2 points to the class imbalance problem in the data set we used. The majority of the data set consists of the "no diabetes" class with a rate of 84.71%, while 15.29% consists of the "diabetes" class. This class imbalance problem directly affects the performance of models to be used in diabetes prediction.

Diabetes Percentage
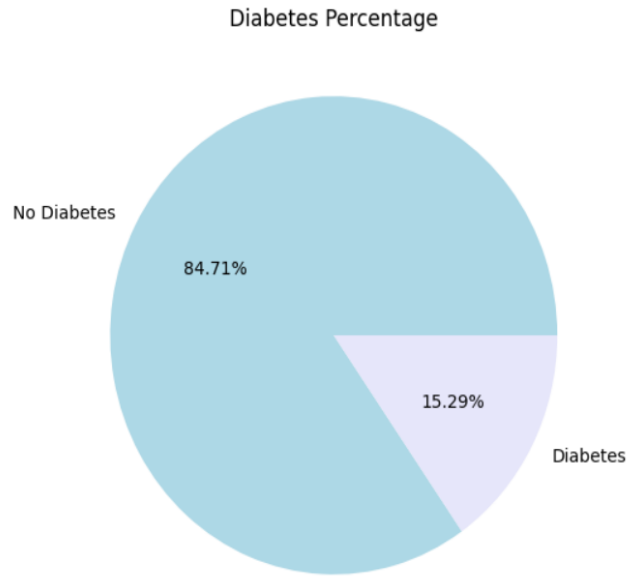
Fig. 2. Distributions between classes.

2.2. Data preprocessing

The presence of duplicate observations in the data was checked and removed. Duplicate observations refer to instances that have identical values across all columns. Removing duplicate observations is performed to prevent bias and ensure accurate data representation [9].

Fig. 3 displays a graph illustrating the correlation between the Diabetes feature and other attributes. Correlation is a statistical measure that quantifies the strength and direction of the relationship between two variables. Values close to 0 indicate a weak or nearly nonexistent correlation between the two variables. A value of 0 signifies no relationship between the two variables. As values move from 0 towards a positive value, they represent a positive relationship (an increase in one variable corresponds to an increase in the other). On the other hand, values moving away from 0 towards -1 indicate a negative relationship (an increase in one variable corresponds to a decrease in the other) [10]. In line with this, features with correlations close to zero were removed from the dataset to improve performance and reduce processing costs. Expressly, nine features named 'AnyHealthcare,' 'Sex,' 'Smoker,' 'NoDocbcCost,' 'CholCheck,' 'MentHlth,' 'Fruits,' 'Veggies,' and 'HvyAlcoholConsump' were excluded from the dataset.
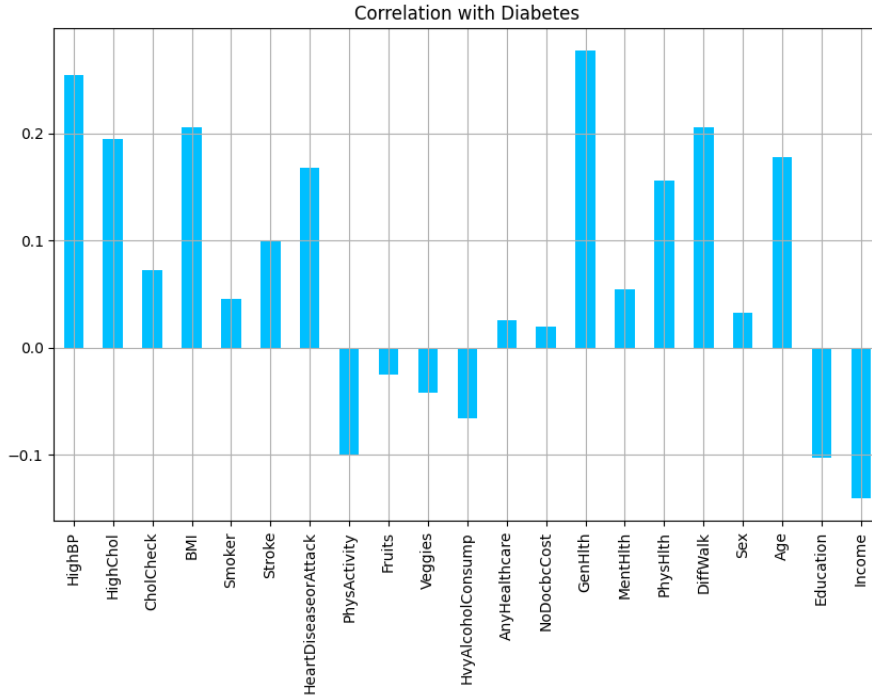
Fig. 3. Correlation with diabetes.

Due to the imbalanced distribution of the dataset, the SMOTE technique was applied. The primary objective of SMOTE is to balance the dataset by oversampling the minority class, thereby enhancing the performance of machine learning models [11].

The following are the SMOTE technique's application stages:

• The k-nearest neighbors are chosen for every instance of the minority class. We selected k = 5 neighbors for our study, and we used the Euclidean distance or another similarity metric to find these neighbors.
• A neighbor is chosen at random from the list of k-nearest neighbors for each minority sample. The delta, or difference, between the selected neighbor and the original sample, is then computed.
• A new synthetic sample is created by randomly selecting a multiplier between 0 and 1, based on the delta value, to determine the size of the difference between the original sample and the chosen neighbor.
• Finally, the first minority class is expanded to include the new synthetic sample.

By increasing the amount of minority class samples using this technique, our study intended to remove class imbalance in the data set. The dataset was divided into 80% for training and 20% for testing after SMOTE was used. The purpose of these preprocessing procedures was to guarantee data quality and get the data ready for modeling activities.

2.3. Machine learning models

Building a model with several learners as opposed to only one is known as ensemble learning [12]. Ensemble learning methods are machine learning approaches that include bagging and boosting. By combining several weak

learners, these techniques provide a prediction or classification model that is more reliable. Although they employ different strategies, both techniques seek to increase model performance. Bagging is short for "bootstrap aggregation." The Bagging technique first creates multiple subsets from the original dataset. A weak learner model is built for each of these subsets. The models make predictions or classifications independently of each other [13]. In other words, the models work in parallel to each other. The final prediction result is obtained by averaging the predictions of each model. The most popular machine learning technique used in Bagging is Random Forest. These methods are used to enhance model performance while handling the characteristics and complexity of the dataset, demonstrating the power of Ensemble Learning.

Boosting, on the other hand, works by sequentially training weak learners and weighting each learner based on the errors of previous learners [14]. Initially, a subset is created from the original dataset, and a base model is built on this subset. Initially, all data points are given equal weights. Errors are calculated, and more weight is assigned to incorrect predictions. Another model is then built, and this model attempts to correct the errors from the previous model. This involves a sequential process [15]. The final model is a weighted average of all the models. Examples of boosting algorithms include GBM (Gradient Boosting Machines), XGBoost (Extreme Gradient Boosting), LightGBM (Light Gradient Boosting Machine), and CatBoost (Categorical Boosting). XGBoost is known for its faster and more scalable structure, which is especially effective in handling large datasets. LightGBM is recognized for its high efficiency and low memory usage, providing advantages in handling large datasets and low-memory systems. CatBoost stands out with its ability to handle categorical variables automatically. LightGBM adopts a leaf-wise growth strategy, requiring fewer steps but more computational power. On the other hand, both XGBoost and CatBoost adopt a level-wise growth strategy, requiring more steps but needing less computational power. In Fig. 4, the difference between bagging and boosting is visualized [15].
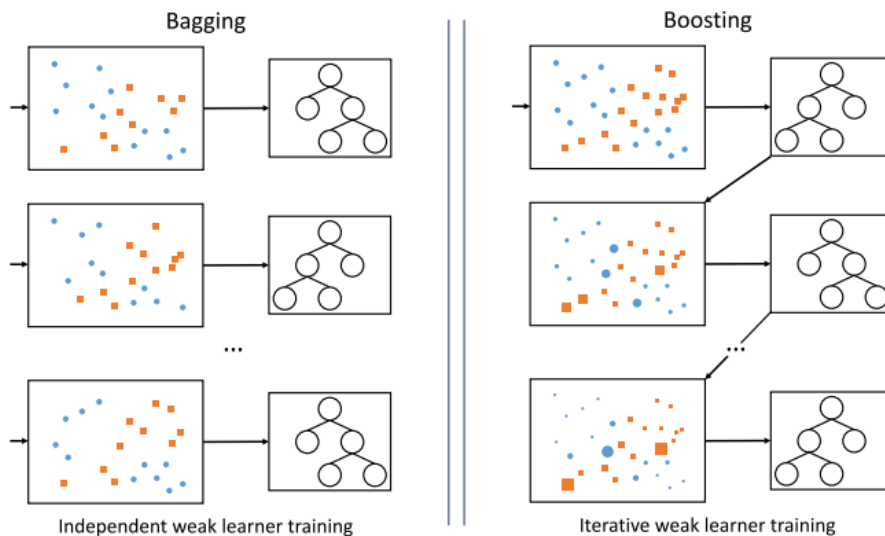
Fig. 4. Bagging vs. Boosting [15].

In this study, predictions were made on Diabetes using ten state-of-art and traditional machine learning models (GBM, XGBoost, LightGBM, CatBoost, Random Forest, Decision Tree, K Nearest Neighbor, Logistic Regression, Gaussian Naïve Bayes, and Ridge Classifier), and the performances of these models were compared. Fig. 5 summarizes the study.
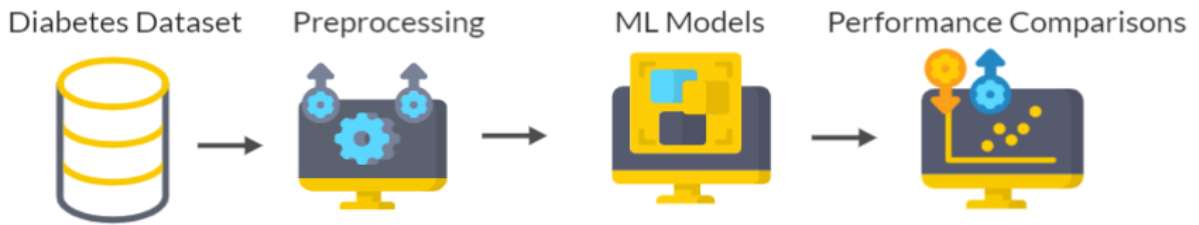
Fig. 5. Workflow of the study.

The ML algorithms used in our study are as follows:

Logistic Regression: Logistic regression is a statistical modeling technique used to predict the probability of a dependent variable. It was first introduced by David Cox in 1958 [16].

Gaussian Naive Bayes: Naive Bayes is a probability-based classification algorithm based on Bayes' theorem. The basic Naive Bayes algorithm became popular in the 1950s and later gained popularity for classification problems [17].

Decision Trees: Decision trees are a modeling technique based on tree structures for classifying data or solving regression problems. The foundation of decision trees dates back to the late 1960s [18].

K Nearest Neighbor (KNN): KNN, is a simple and effective algorithm used for classification and regression problems by examining the K nearest neighbors of a data point [19].

Ridge Classifier: The Ridge classifier is an extension of ridge regression and addresses classification problems [20].

Random Forests: Random Forests were introduced by Leo Breiman in a paper titled "Random Forests" in 2001. Random Forests are an algorithm that addresses complex classification problems by combining multiple decision trees [21].

Gradient Boosting Machines: Gradient boosting methods were developed in the late 1990s and gained popularity. They primarily combine weak learners to create a robust model [22].

XGBoost: XGBoost was introduced by Chen and Guestrin in 2014. XGBoost is a fast and effective gradient-boosting framework [23].

LightGBM: LightGBM, introduced by Microsoft in 2016, is a machine-learning library that provides fast and distributed gradient boosting for large datasets [24].

CatBoost: CatBoost, introduced by Yandex in 2017, is a gradient-boosting library that directly handles categorical variables and reduces overfitting [25].

Machine learning algorithms such as GBM, XGBoost, LightGBM, CatBoost, Random Forest, Decision Tree, K Nearest Neighbor, Logistic Regression, Gaussian Naïve Bayes, and Ridge Classifier represent various learning methods with different features and use case scenarios. Ensemble methods like GBM, XGBoost, LightGBM, CatBoost, and Random Forest create more robust and generalizable models by combining weak models. However, the critical differences among these algorithms emerge in terms of speed, scalability, categorical variable handling capabilities, and growth strategies. Decision Tree can classify or regress a dataset by creating a decision tree. K Nearest Neighbor performs classification or Regression based on the similarities of data points. Logistic Regression is used for binary classification problems, while Gaussian Naïve Bayes is a probability-based classification algorithm. Ridge Classifier, on the other hand, is a linear classifier that stands out, especially with regularization. During our study, we experimented with and compared the performance of these ten different machine-learning models for predicting diabetes.

3. Experimental results

We conducted the experiments in two stages. Initially, we trained and tested the models on the dataset without applying the SMOTE technique. Subsequently, to enhance model performance, we applied the SMOTE technique and compared the accuracy rates of the models. We have presented both scenarios in Table 1. According to this table, we observed an improvement in the models' performance after applying SMOTE. In the comparisons conducted without SMOTE, the highest performance was achieved by the LightGBM model. However, when SMOTE was applied, the model with the highest performance had an accuracy rate of 0.9005, attributed to the CatBoost model.

Table 1. Performance comparisons of models.

Model without SMOTE	Accuracy Score	Model with SMOTE	Accuracy Score
LightGBM	0.8518	CatBoost	0.9005
GBM	0.8510	XGBoost	0.8999
XGBoost	0.8504	RF	0.8963
CatBoost	0.8502	LightGBM	0.8935
LR	0.8482	DT	0.8629
RC	0.8481	GBM	0.8610
RF	0.8318	KNN	0.8232
KNN	0.8314	LR	0.7351
DT	0.7947	RC	0.7342
GNB	0.7815	GNB	0.6959

In Fig. 6, the models' training times and accuracy rates are displayed graphically. According to this graph, when looking at the models trained and tested without applying SMOTE, the highest accuracy rate belongs to the LightGBM model, and the training speed of this model is higher than most of the other models. On the other hand, CatBoost has the highest accuracy rate for the models trained with SMOTE, but its training time is slower than the other models.

(a) Performances of models without SMOTE

(b) Performances of models with SMOTE

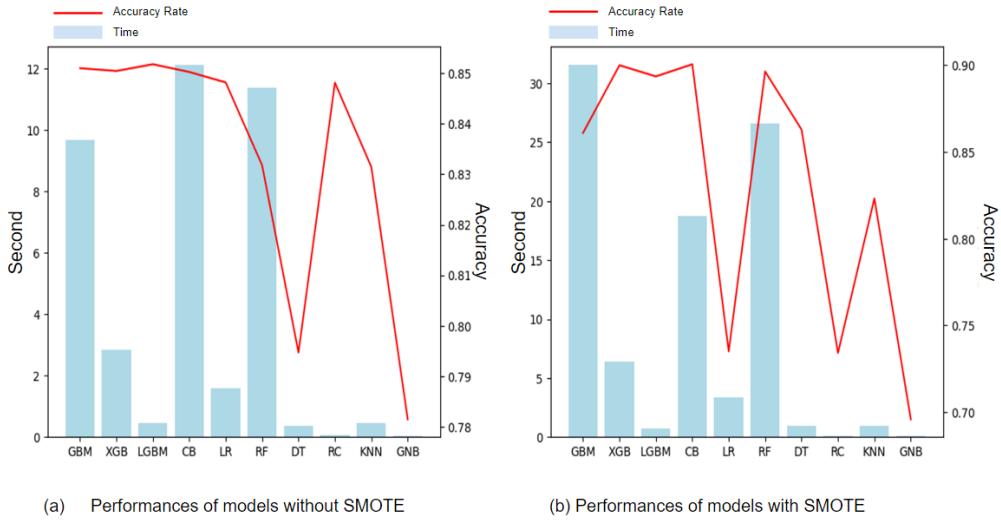Fig. 6. Comparison of models' performance and training time.

The AUC (Area under the ROC Curve) – ROC (receiver operating characteristic curve) graph of the models applied to SMOTE is presented in Fig. 7. The AUC-ROC curve visualizes the sensitivity (true positive rate) and specificity (true negative rate) of the classification model against different threshold values.
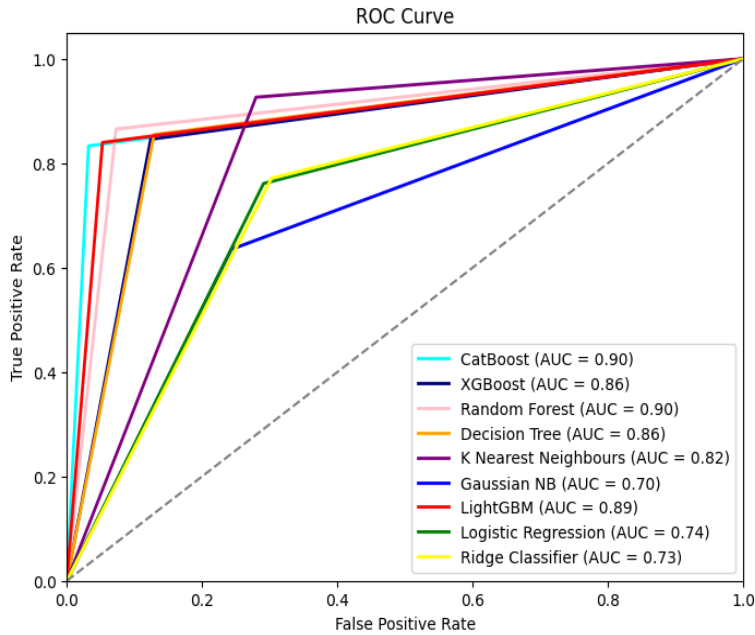

Fig. 7. AUC – ROC curve.

4. Conclusions

This study evaluated and compared the performance of 10 different machine learning models, including state-of-art models, to identify diabetes. Without applying the SMOTE technique to the dataset, the model that demonstrated the highest performance achieved an accuracy of 85.18%, attributed to the LightGBM model. Furthermore, it was noted that this model's training time was shorter than most of the other models. Due to the imbalanced nature of the dataset and the aim to enhance performance, applying the SMOTE technique to the data resulted in the CatBoost algorithm attaining the highest accuracy rate of 90.05%.

This comparative analysis of machine learning models provides valuable insights for selecting the most suitable model for addressing classification problems. Nevertheless, certain limitations and opportunities for future research should be acknowledged. Firstly, hyperparameter tuning and model optimization could enhance results. Expanding the dataset with more extensive and diverse sampling may improve the model's generalization capabilities. Collaborating with healthcare professionals and diabetes experts to interpret and validate features and outcomes from a clinical perspective is crucial. This interdisciplinary approach can unlock the potential of machine learning models to deliver real value in clinical applications.

In conclusion, this study successfully demonstrated the efficacy of machine learning models in diabetes identification. Future research endeavors should explore advanced methodologies and foster collaborations to achieve superior performance and increased applicability in clinical settings.

Acknowledgements

References

[1] A. D. Deshpande, M. Harris-Hayes, and M. Schootman, "Epidemiology of diabetes and diabetes-related complications," *Phys. Ther.*, vol. 88, no. 11, pp. 1254-1264, Nov. 2008, doi: https://doi.org/10.2522/ptj.20080020.
[2] H. D.McIntyre, P. Catalano, C. Zhang, G. Desoye, E. R. Mathiesen, and P. Damm, "Gestational diabetes mellitus," *Natur. Rev. Dis. Prim.*, vol. 5, no. 1, pp. 47, Jul. 2019, doi: https://doi.org/10.1038/s41572-019-0098-8.
[3] İ. Akgül, Ö. Çağrı Yavuz, and U. Yavuz, "Deep Learning Based Models for Detection of Diabetic Retinopathy," *Tehnički glasnik*, vol. 17, no. 4, pp. 581-587, Dec. 2023, doi: https://doi.org/10.31803/tg-20220905123827.
[4] N. Yuvaraj and K.R. SriPreethaa, "Diabetes prediction in healthcare systems using machine learning algorithms on Hadoop cluster," *Clust. Comp.*, vol. 22, no. 1, pp. 1-9, Jan. 2019, doi: https://doi.org/10.1007/s10586-017-1532-x.
[5] Z. Xie, O. Nikolayeva, J. Luo, and D. Li, "Peer reviewed: building risk prediction models for type 2 diabetes using machine learning techniques," *Prev. Chro. Dis.*, vol. 16, Sep. 2019, doi: 10.5888/pcd16.190109.
[6] S. Wei, X. Zhao, and C. Miao, "A comprehensive exploration to the machine learning techniques for diabetes identification," *in 2018 IEEE 4th World Forum on Int. of Things*, 2018, pp. 291-295, doi: 10.1109/WF-IoT.2018.8355130.
[7] A. Yahyaoui, A. Jamil, J. Rasheed, and M. Yesiltepe, "A decision support system for diabetes prediction using machine learning and deep learning techniques," *in 2019 1st Inter. Inform. and Soft. Eng. Conf.,* 2019, pp. 1-4, doi: 10.1109/UBMYK48245.2019.8965556.
[8] Diabetes Health Indicators Dataset, https://www.kaggle.com/datasets/alexteboul/diabetes-health-indicators-dataset (accessed December 12, 2023).
[9] M. Crowther, W. Lim, and M. A. Crowther, "Systematic review and meta-analysis methodology," *The Jour. of the Amer. Soc. of Hemat.*, vol. 116, no. 17, pp. 3140-3146, Oct. 2010, doi: https://doi.org/10.1182/blood-2010-05-280883.
[10] S. Pandey, "Principles of correlation and regression analysis," *Jour. of the prac. of cardio. Sci.*, vol. 6, no. 1, pp. 7-11, Apr. 2020, doi: 10.4103/jpcs.jpcs_2_20.
[11] N. V. Chawla, K. W. Bowyer, L. O. Hall, and W. P. Kegelmeyer, "SMOTE: synthetic minority over-sampling technique," *Jour. of artif. Intel. Res.*, vol. 16, pp. 321-357, Jun. 2002, doi: https://doi.org/10.1613/jair.953.
[12] X. Dong, Z. Yu, W. Cao, Y. Shi, and Q. Ma, "A survey on ensemble learning," *Front. of Comp. Sci.*, vol. 14, pp. 241-258, Apr. 2020, doi: https://doi.org/10.1007/s11704-019-8208-z.
[13] L. Breiman, "Bagging predictors," *Mach. Learn.*, vol. 24, pp. 123-140, Aug. 1996, doi: https://doi.org/10.1007/BF00058655.
[14] R. E. Schapire, "A brief introduction to boosting," *Ijcai*, Vol. 99, No. 999, pp. 1401-1406, 1999.

[15] S. González, S. García, J. Del Ser, L. Rokach, and F. Herrera, "A practical tutorial on bagging and boosting based ensembles for machine learning: Algorithms, software tools, performance study, practical perspectives and opportunities," *Infor. Fus.*, vol. 64, pp. 205-237, Dec. 2020, doi: https://doi.org/10.1016/j.inffus.2020.07.007.

[16] D. R. Cox, "The regression analysis of binary sequences," *Jour. of the Roy. Stat. Soc. Ser. B: Stat. Meth.*, vol. 20, no. 2, pp. 215-232, Jul. 1958, doi: https://doi.org/10.1111/j.2517-6161.1958.tb00292.x.

[17] S. Jayachitra, and A. Prasanth, "Multi-feature analysis for automated brain stroke classification using weighted Gaussian naïve Bayes classifier," *Jour. of Circ. Sys. and Comp.*, vol. 30, no. 10, pp. 2150178, 2021, doi: https://doi.org/10.1142/S0218126621501784.

[18] C. Kingsford and S. L. Salzberg, "What are decision trees?," *Nat. Biotech.*, vol. 26, no. 9, pp. 1011-1013, Sep. 2008, doi: https://doi.org/10.1038/nbt0908-1011.

[19] S. Uddin, I. Haque, H. Lu, M. A. Moni, and E. Gide, "Comparative performance analysis of K-nearest neighbor (KNN) algorithm and its different variants for disease prediction," *Sci. Rep.*, vol. 12, pp. 6256, Apr. 2022, doi: https://doi.org/10.1038/s41598-022-10358-x.

[20] S. Priyadarshinee and M. Panda, "Cardiac disease prediction using smote and machine learning classifiers," *Jour. of Pharma. Neg. Res.*, vol. 13, no.8, pp. 856-862, Nov. 2022, doi: https://doi.org/10.47750/pnr.2022.13.S08.108.

[21] L. Breiman, "Random forests," *Mac. Learn.*, vol. 45, pp. 5-32, Oct. 2001, doi: https://doi.org/10.1023/A:1010933404324.

[22] A. Natekin and A. Knoll, "Gradient boosting machines, a tutorial," *Front. in Neurorob.*, vol. 7, pp. 21, Dec. 2013, doi: https://doi.org/10.3389/fnbot.2013.00021.

[23] T. Chen, T. He, M. Benesty, V. Khotilovich, Y. Tang, H. Cho, and T. Zhou, "Xgboost: extreme gradient boosting," R package version 0.4-2, vol. 1, no. 4, pp. 1-4, 2015.

[24] G. Ke, Q. Meng, T. Finley, T. Wang, W. Chen, W. Ma, and T. Y. Liu, "Lightgbm: A highly efficient gradient boosting decision tree," *Adv. in Neur. Info. Process. Sys.*, 30, 2017.

[25] L. Prokhorenkova, G. Gusev, A. Vorobev, A. V. Dorogush, and A. Gulin, "CatBoost: unbiased boosting with categorical features," *Adv. in Neur. Info. Process. Sys.*, 31, 2018.

ARAŞTIRMA MAKALESİ/RESEARCH ARTICLE

Lorentz metrik uzayı üzerine

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Öz

Bu çalışma, kompakt-olmayan 4-manifold üzerindeki tüm C^2 Lorentz metriklerinin kümesini ele almaktadır. Bu metrikler, manifoldun fiziksel uzay-zaman yapısını tanımlayan önemli öğelerdir. Manifold üzerindeki Lorentz metriklerinin kümesi, Whitney C^2 topolojisi ile verilmiştir. Bu topoloji, manifoldun üzerinde tanımlanan vektör alanları arasındaki kesitlerin topolojisini tanımlar. Bu tanım, Lorentz metriklerinin manifoldun topolojik özelliklerini yansıttığını ve analiz etmek istediğimiz uzay-zaman yapısının doğru bir çerçevesini sağladığını gösterir. Özellikle space-like manifoldların global özelliklerini ve tekillik teoremlerini tartışmak için önemli bir temel oluşturur. Space-like manifoldlar, uzay-zamanın fiziksel özelliklerini tanımlayan ve genel görelilik teorisinde önemli bir rol oynayan yapılar arasındadır. Bu çalışma, bu manifoldların genel özelliklerini incelemek ve tekillik teoremlerini daha derinlemesine anlamak için doğru bir çerçeve sunar. Sonuç olarak, Robertson-Walker büyük patlamasını Lorentz metrikleri ile ele alan açıklamalar sunulmaktadır. Bu açıklamalar, metrik tensörün yeterince küçük, sonlu C^2 pertürbasyonları altında kararlı olduklarını göstermektedir. Bunlar büyük patlamanın evrenin genel davranışını nasıl etkilediğini ve tekilliklerin nasıl oluştuğunu anlamak için önemli bir adımdır. Lorentz metrik uzaylarında yapılan analizler ve sonuçlar uzay-zaman yapısının daha iyi anlaşılmasına katkıda bulunur.

Anahtar Kelimeler: Lorentz Metrik, Lorentz Metrik Uzayı, Metrik

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1. Giriş

Lorentz metrikleri, özel görelilik teorisinde uzay-zamanın geometrisini tanımlamak için kullanılan matematiksel yapılar ve araçlardır. Uzay-zamanın dört boyutlu bir manifold olduğu düşünüldüğünde, Lorentz metrikleri bu manifold üzerindeki her noktada metrik tensör olarak tanımlanır. Bu metrik tensör, uzay-zamanın her noktasında metrik ölçülerini, zaman ve uzayın nasıl birbirine bağlandığını açıklayan bir matematiksel ifade sunar. Lorentz metriklerinin uzayında, zaman ve uzay boyutları arasındaki ilişki, özel görelilikte öngörülen ışık hızının sabitliği prensibine dayanır.

Bu metrikler, genellikle zamana bağlı olan uzayda bir zaman benzeri boyut ve üç uzaysal boyut içerir. Bu şekilde, Lorentz metrikleri, özel görelilik teorisinin temel prensiplerini ve zaman ile uzayın nasıl birleştiğini açıklayarak, görelilik teorisindeki olayları matematiksel olarak modellemek için kullanılır. Lorentz metriklerinin uzayında, önemli kavramlardan biri de spacelike, timelike ve lightlike gibi farklı hiper yüzeylerdir. Bu hiperyüzeyler, uzay-zamanın farklı bölgelerini ve olayları ayıran farklı özellikleri temsil eder. Spacelike hiperyüzeyler, uzaydaki noktaların zaman benzeri vektörlerle ayrılamayacağı bölgeleri ifade ederken, timelike hiperyüzeyler zamanın geçtiği bölgeleri temsil eder. Lightlike hiperyüzeyler ise ışığın hareket ettiği bölgeleri gösterir. Lorentz metriklerinin uzayında, farklı geometrik yapılar ve tensörler kullanılarak uzay-zamanın özellikleri matematiksel olarak analiz edilir. Bu analizler, özel görelilik teorisinin temel prensiplerini ve fiziksel olayları anlamak için önemli bir araç sağlar. Bu makalede, Lorentz metriklerinin uzayında kullanılan kavramları, tensörleri ve geometrik yapıları detaylı bir şekilde ele alınarak ve uzay-zamanda yaşanan olayların matematiksel olarak nasıl tanımlanabileceği incelenmiştir. Ayrıca, spacelike, timelike ve lightlike hiperyüzeylerin önemini ve uzay-zamandaki olayları nasıl etkilediği açıklanmıştır. Lorentz metrik uzayında yapılan çalışmalar, modern fizik ve görelilik teorisi açısından büyük bir öneme sahiptir ve bu alanlardaki araştırmaların temelini oluşturur [1-5].

2. Temel kavramlar

Bu bölümde, Whitney haritalama topolojileri, jet demetlerinin incelenmesi ve gerekli matematiksel mekanizma tanıtılmıştır. Whitney haritalama topolojileri, düzgün fonksiyonların ve vektör alanlarının topolojik özelliklerini taşıyan bir yapıdır. Bu topolojiler, sürekli dönüşümlerin ve diferensiyel operatörlerin analizini kolaylaştırır. Whitney topolojileri, düzgün fonksiyonlar ve vektör alanları arasındaki ilişkiyi sağlar. Aynı zamanda birbiriyle uyumlu Lorentz metrikleri ve konformal yapılarla ilişkilidir. Lorentz metrikleri, zaman-mekanın geometrik özelliklerini tanımlamak için kullanılan matematiksel yapılar olarak önemlidir. Konformal yapılar ise, ölçek değişimlerine karşı invaryant olan geometrik yapıları ifade eder. Bu bağlamda, Lorentz metrikleri ve konformal yapılar ile tutarlı olan Whitney topolojileri, bir Lorentz metriğini eşdeğerlik sınıfına sürekli bir harita olarak gönderen haritaların varlığını ifade eder. Böylece, Lorentz metriklerinin geometrik özelliklerini ve konformal yapıların ölçek değişimine karşı invaryantlığını koruyan topolojik bir yapı sağlar. Whitney topolojileri, analiz ve geometri alanlarında farklı uygulamalara sahiptir ve bu alanlarda yapılan çalışmalarda önemli bir rol oynamaktadır. Çalışma boyunca bütün manifoldlar $\mathbb{C}$ Hausdorff ve para-kompakttır; Ayrıca M, kompakt olmayan 4-boyutlu manifoldu ifade eder. $S \rightarrow M$, iki kovaryant simetrik tensörlerin vektör demeti ve $L \rightarrow M$, ikinci dereceden demeti olsun. L'nin tüm $\mathbb{C}^k$ bölümlerinin kümesi $\mathbb{C}^k(L)$ ile gösterilir; bu kümenin herhangi bir elemanına $\mathbb{C}^k$ *Lorentz metrik* denir, topolojileştirilmek istenilen kümedir. Bunu yapmadan önce, görelilik teorisinde ortaya çıkan ilginç geometrik nesnelerin çoğunun, tamamen spacetime konformal yapısı tarafından belirlendiği ifade edilmiştir [6]. Ayrıca S: $S \backslash \{0\}$ elde edilen demeti gösterir.

Bu problemin çözümü için temel kavramlar aşağıdaki şekilde açıklanabilir;
1. $\mathbb{C}$, bütün manifoldların kompleks sayılar kümesini temsil eder.
2. Hausdorff: Bir topolojik uzayın Hausdorff olması, her iki noktanın birbirinden ayrılabilmesi anlamına gelir. Bu özellik, uzayın ayrık ve net bir yapıya sahip olduğunu ifade eder.

3. Para-kompakt: Bir topolojik uzayın para-kompakt olması, uzayın her noktasını içeren bir açık küme sistemiyle kaplanabileceği anlamına gelir. Bu özellik, uzayın düzenli ve düzgün bir şekilde bölünebileceğini ifade eder.

4. M: Bu sembol, kompakt olmayan dört boyutlu bir manifoldu temsil eder. Manifold, lokal olarak gerçek sayılarının dört boyutlu bir uzayına benzer.

5. S→M: S'in M üzerindeki bir vektör demeti olduğunu ifade eder. Vektör demeti, her noktada bir vektör uzayı bulunan bir yapıdır.

6. L→M: L'in M üzerindeki ikinci dereceden bir demet olduğunu ifade eder. İkinci dereceden demet, her noktada bir ikinci dereceden tensör uzayı bulunan bir yapıdır.

7. $C^k(L)$: L'nin tüm C^k bileşenlerinin bir kümesini temsil eder. Bu kümenin herhangi bir elemanına C^k Lorentz metrik denir.

8. Lorentz metrik: Lorentz metriği, dört boyutlu bir manifold üzerinde tanımlanan bir metrik tensördür. Bu metrik, özel görelilik teorisinde uzay-zamanın geometrisini açıklamak için kullanılır.

9. Görelilik teorisinde ortaya çıkan geometrik nesnelerin çoğunun, tamamen space-time konformal yapısı tarafından belirlendiği belirtilir. Bu ifade, görelilik teorisindeki ilginç geometrik nesnelerin çoğunun, space-time konformal yapısı tarafından tamamen belirlendiğini vurgular.

10. Konformal yapılar kümesi de topolojileştirilebilirse işlemler kolaylaşacaktır. Bu ifade, konformal yapılar kümesinin topolojik olarak tanımlanabileceği ve bunun işlem kolaylığı sağlayacağını gösterir.

11. S\{0} ile elde edilen demet $\hat{S}$ ile belirtilir.

12. Dokuz küreye göre difeomorfik olan bir Q demeti üzerine $\hat{S}$'nin bir τ geri çekilmesinin varlığını ifade eder.

Bu denklemler, temel kavramları ve terminolojiyi açıklamak için kullanılan ifadeleri temsil etmektedir. Bu açıklamalar, genel anlamda problemin bağlamını ve kavramsal temellerini anlamak için yardımcı olmaktadır. $L \longrightarrow M$, jet demeti aşağıdaki şekilde tanımlanır:

$$L = \{ (x, v) \mid x \in M, v \in T_x M \}. \tag{1}$$

g: Lorentz metriği M kümesinde $g: M \to \mathbb{R}_{4x4}$ şekilde tanımlanır.
U(g): Uyumlu dönüşümler kümesi $\phi: M \to M$ olacak şekilde tanımlanan haritalar kümesi olarak ifade edilir:
$\phi^*(g) = g$
T(g): Uyumlu topolojiler kümesi, g metriğiyle uyumlu yapıları içeren M üzerindeki uyumlu topolojiler kümesi olarak ifade edilir.

Bu denklemler kullanılarak Lorentz metrikleri, uyumlu yapılar ve topolojiler arasındaki ilişki belirlenebilir ve bu ilişkiyle ilgili denklemler ve problemler çözülebilir [7]. Bu sonuçları elde etmek ve denklemle ilgili özellikleri anlamak için demet teorisi, topoloji ve matematiksel analiz teknikleri kullanılabilir.

Uzay-zaman bağlamında, bahsedilen denklemler ışığın davranışı, uzay zaman eğriliği ve uzay zaman metrikleri ile topoloji arasındaki ilişki gibi uzay zaman geometrisinin çeşitli yönlerini incelemek ve analiz etmek için kullanılabilir [8]. İşte bu denklemlerin uzay-zaman alanında nasıl uygulanabileceğine dair bazı örnekler:

1. Eğrilik ve Geometri: g metriği, uzay-zaman eğriliğini tanımlamak için kullanılabilir. Metrik tensörün bileşenlerini analiz ederek, uzay-zamandaki farklı noktalardaki eğriliği belirlenebilir. Uzay-zaman manifoldunun geometrisi anlaşılır hale getirilebilir.

2. Lorentz Dönüşümleri: U(g) kümesi, uzay-zamanda tutarlı dönüşümlerin grubunu temsil eder. Lorentz dönüşümleri, özel görelilikte önemli bir rol oynar, ölçümlerin ve gözlemlerin farklı referans çerçeveleri altında nasıl değiştiğini tanımlar. Lorentz dönüşümlerinin özelliklerini inceleyerek, uzay-zaman simetrileri ve değişmezlik prensipleri anlaşılır hale getirilebilir.

3. Topoloji ve Tutarlı Yapılar: T(g) kümesi, verilen g metriği ile uyumlu uzay-zamandaki tutarlı topolojileri temsil eder. Bu, bağlantılılık, sıkılaşma ve karmaşık döngülerin veya deliklerin varlığı gibi farklı topolojik özelliklerin uzay zamanda keşfedilmesine olanak sağlar. Uzay-zamanın topolojisini anlamak, fiziksel olguların küresel özelliklerini ve davranışlarını incelemek açısından önemlidir.

4. Fiziksel Denklemler: Jetlerin, metriklerin ve tutarlı yapıların kavramlarını birleştirerek, madde ve alanların

davranışını kontrol eden fiziksel denklemler türetilebilir ve çözülebilir. Bu denklemler, genel görelilikteki Einstein alan denklemleri gibi, uzay-zamanın eğriliğini madde ve enerjinin dağılımıyla ilişkilendirir.

Dokuz küreye göre difeomorfik olan bir Q demeti üzerine S 'nin bir τ geri çekilmesi var ise yerel koordinatlarda $\tau(u^i, S_{ab}) \rightarrow (u^i, S_{ab}/S)$ ile verilir [9-10], burada $a \leq b$ ve

$$S = (\sum_{m \leq n}(S_{mn})^2)^{1/2} \tag{2}$$

Uzay-zaman bağlamında, $\tau(u^i, S_{ab}) \rightarrow (u^i, S_{ab}/S)$ denklemi, uzay-zaman manifoldundaki vektörler ve tensörler arasında bir dönüşümü veya işlemi temsil etmek için kullanılır. Uzay-zaman bağlamında olası bir uygulama şöyledir:

u^i: Dört-boyutlu uzay-zamanda bir nesnenin hızını tanımlayan dört hız vektörünü temsil eder.

S_{ab}: a ve b indisleriyle gösterilen bir tensörü temsil eder. Uzay-zamanda, tensörler genellikle enerji-momentum tensörü veya eğrilik tensörü gibi fiziksel nicelikleri tanımlamak için kullanılır.

S : Bir skaler değeri temsil eder. Verilen denklemde, bir normalizasyon faktörü olarak işlev görür. Skaler S, tensör S_{ab}'ın bileşenlerinin karelerinin toplamının karekökü olarak hesaplanabilir. Bu hesaplama, tensörün genel büyüklüğünü veya boyutunu belirlemeye yardımcı olur. Tensör S_{ab}'ın her bir bileşenini skaler S ile böldüğümüzde, denklem bir normalizasyon veya ölçeklendirme işlemi gerçekleştirir. Bu normalizasyon, farklı büyüklüklere sahip tensörleri karşılaştırmak veya uzay-zaman hesaplamalarında tutarlı ölçeklendirme sağlamak gibi çeşitli amaçlar için kullanışlıdır.

$J^K(M,E) \rightarrow M \times E$, jet demeti $J^K(M,E)$'den görüntü uzayı $M \times E$'ye bir eşlemeyi temsil eder. Zaman-mekân bağlamında bu denklem şu şekilde ifade edilebilir: M, zaman-mekânın temel demetini temsil eder ve zaman-mekânın geometrik yapısını tanımlar. E, demet içindeki her nokta ile ilişkilendirilebilen bir vektör uzayını veya fiziksel bir alanı temsil eder. Ayrıca E'de değer alan fonksiyonların türevlerini içeren bir matematiksel kavramdır. Zaman-mekân alanında, bu denklem, M'nin geometrik özellikleri ile E tarafından temsil edilen ek yapılar veya alanlar arasındaki ilişkiyi incelemek için kullanılabilir. Bu eşleme analiz edilerek, zaman-mekânda fiziksel alanların davranışını, kalibrasyon simetrilerini ve diğer geometrik özelliklerini anlamak mümkündür.

U$\subseteq J^K(E)$ ve $j^K(f)(M) \subseteq$ U, uzay-zaman ve jet demetleri olarak tanımlandığında; U, jet demeti $J^K(E)$'nin bir alt kümesini temsil eder. Burada $J^K(E)$, ek yapı veya E ile ilişkili K-jet demetini gösterir. U, belirli koşulları veya kısıtlamaları sağlayan belirli unsurları içeren bir jet demeti alt kümesidir. Öte yandan, $j^K(f)(M)$, M'de tanımlanan bir f fonksiyonunun K-jet uzantısını temsil eder. Bu fonksiyonu ve onun K. mertebeye kadar olan türevleri hakkında bilgi içerir. $j^K(f)(M)$, jet demeti $J^K(E)$'nin bir alt kümesidir ve M'deki her noktanın K-jet değerlerine karşılık gelen elemanları içerir.

$j^K(f)(M)$ alt kümesinin U alt kümesi içinde olduğunu ifade eder. Bu durum, M'deki her noktanın K-jet değerlerinin U tarafından belirlenen koşulları sağladığını gösterir. Başka bir deyişle, $j^K(f)(M)$ elemanları, U tarafından tanımlanan koşullarla sınırlıdır. Bu denklem, uzay-zaman ve jet demetlerinin çalışmasında fonksiyonların ve türevlerinin davranışı üzerinde belirli özellikleri veya kısıtlamaları belirtmek için yaygın olarak kullanılır. Fiziksel alanların, kalibre simetrilerinin veya uzay-zaman manifoldlarında tanımlanan diğer matematiksel nesnelerin davranışını tanımlamak ve analiz etmeye yardımcı olur. U, $J^K(E)$ ve $j^K(f)(M)$ öğeleri arasındaki ilişkiyi göz önünde bulundurarak, uzay-zaman bağlamında incelenen sistemin yapısı ve özellikleri kavranılabilir [6].

3. Einstein denklemleri

Einstein denklemleri, genel görelilik teorisinde uzay-zaman geometrisini açıklar ve uzay-zamanın enerji ve madde içeriğiyle ilişkili olduğunu ifade eder. Bu bölümde, Einstein denklemlerinin izol çözümleri olmadığı belirtilmektedir. Yani, bu denklemleri tam olarak çözmek ve analitik olarak kapalı çözümler bulmak mümkün değildir. Bunun yerine, genellikle sayısal veya yaklaşımsal yöntemler kullanılarak çözümler elde edilir.

Bir Lorentz metriğinin 2-jetini Ricci tensörünün 0–jetine eşleyen, Ric: $J^2(L) \mapsto J^°(S)$ ifadesi, Einstein denklemlerine örnek temsil etmektedir. Einstein denklemleri, uzay-zamanın geometrisini tanımlayan metrik tensör ve bu tensöre bağlı olan enerji ve madde dağılımını ifade eden enerji-momentum tensörü arasındaki ilişkiyi açıklar. Bu denklemler, genel görelilik teorisi çerçevesinde Einstein tarafından formüle edilmektedir. Örnek olarak verilen ifade, bir Lorentz metriğinin 2-jetini Ricci tensörünün 0-jetine eşleyen bir ilişkiyi göstermektedir. Burada, $J^2(L)$ Lorentz metriğinin 2-jetini temsil ederken, $J^°(S)$ ise Ricci tensörünün 0-jetini temsil etmektedir. Bu ilişki, Lorentz metriği ve Ricci tensörü arasında bir bağlantıdan yola çıkarak uzay-zamanın geometrisini ve enerji-momentum dağılımını açıklamaya yardımcı olmaktadır [6].

4. Uzay-zamanın global özelliklerinin kararlılığı

Bu kısımda, uzay zaman manifoldlarının belirli global özelliklerinin kararlı olduğu ve genel görelilik teorisiyle uyumlu olduğu belirtilmektedir. Bu özellikler, uzay-zamanın evrimi ve davranışı hakkında bilgi sağlamaktadır. Ayrıca teorik fizik, matematik ve kozmoloji alanlarında çalışan araştırmacılar arasında ilgi görmektedir. Burada Robertson-Walker metriklerini kullanarak uzay-zamana ait metriklerin global özelliklerinin kararlılığını açıklanmaktadır. Robertson-Walker metrikleri, evrenin genişleme modelini tanımlayan kozmolojik metriklerdir. Bu ifadeye göre, belirli bir Robertson-Walker metriği kullanılarak, zaman (t), yarıçap (r), eğim açısı (θ) ve dönme açısı (φ) koordinatlarına bağlı olarak evrenin genişlemesini ve büyük ölçekli davranışını açıklamak mümkündür [11]. Bu metrikler aşağıdaki formülle tanımlanır:

$$g(t, r, \theta, \varphi) = dt^2 - R(t)^2 \left(dr^2/(1-kr^2) + r^2 d\theta^2 + \sin^2\theta d\varphi^2 \right). \tag{3}$$

Bu metriklerin özellikleri ve davranışı hakkında temel bilgilerin olduğu varsayılmaktadır. Belirli bir Robertson-Walker metriği, enerji-momentum tensörünün mükemmel bir akışkan olduğu ve R(t) için alan denklemlerinin çözümlendiği varsayımıyla elde edilmektedir. Enerji-momentum tensörü, yoğunluk (ρ) ve basınç (p) gibi özelliklere sahip olan bir akışkanın özelliklerini temsil eder. Bu ifade, Robertson-Walker metriklerinin kullanılarak elde edilen belirli metriklerin, evrenin genişlemesinin ve davranışının belirli koşullar altında nasıl modellendiğini ve tanımlandığını açıklamaktadır. Bu metriklerin özellikleri ve alan denklemleri çözüldüğünde elde edilen çözümler, evrenin büyük ölçekli davranışının stabilite ve kararlılık özelliklerini belirlemeye yardımcı olur [11].

5. G -tekillikler

G-tekillikleri, Einstein denklemlerinin çözümlerinde ortaya çıkan ve uzay-zaman eğriliğin sonsuz derecede büyük olduğu veya fiziksel niceliklerin aşırı davranış sergilediği bölgeleri gösteren noktalardır. Bu tekillikler genellikle evrenin teorik tanımı içinde istisnai veya anormal koşulları temsil eder. Lorentz metrikleri, G-tekilliklerinin oluşumunu ve davranışını analiz etmede çok önemli bir rol oynar. Bu metrikler kullanılarak tekilliklerin özelliklerini ve karakteristikleri araştırılabilir ve temel fiziğe ilişkin değerli bilgiler edinilebilir. G-tekilliklerinin doğasını anlamak, aşırı koşullarda uzay-zamanın davranışı hakkında temel ipuçları sağladıkları ve mevcut fiziksel teorileri anlamamıza yardımcı olur. G-tekilliklerinin incelenmesi, kara delikler, yerçekimsel çökmeler ve evrenin ilk aşamaları gibi büyüleyici olayları keşfetmemize olanak tanır. Lorentz metrikleri, bu karmaşık sistemleri tanımlamak ve analiz etmek için gerekli matematiksel çerçeveyi sağlayarak, tekilliklerin yakınında uzay-zamanın özelliklerinin incelemesine, ufukların doğası, yerçekimi dalgaları, madde ve enerjinin davranışı dahil olmak üzere ilişkili fiziksel olayların araştırılmasına olanak tanır. G-tekilliklerini incelemesi ile elde edilen sonuçlar, geleneksel fizik yasalarının işlemediği bölgelerde evrenin davranışını daha iyi açıklayabilen teorilerin ve modellerin geliştirilmesine katkıda bulunur [12-13].

6. Büyük patlamanın kararlılığı

Lorentz metrikleri, zamanın evrimini, uzayın genişlemesini ve Büyük Patlama teorileri bağlamında evrenin ilk aşamalarında meydana gelen dinamik süreçleri anlamak için temel araçlar olarak hizmet eder. Bu metrikler, uzay-zaman geometrisinin matematiksel bir temsilini sağlayarak, Büyük Patlama ile ilişkili fiziksel olayların anlaşılmasına ve yorumlanmasına olanak tanır. Lorentz metrikleri kullanılarak Büyük Patlamanın kararlılığı hakkında fikir edinilebilir. Kararlılık, evrenin ilk anlarının teorik tanımının tutarlılığı ve sağlamlığı anlamına gelir. Lorentz metrikleri tarafından tanımlandığı şekliyle uzay-zaman dinamiklerinin ve özelliklerinin Büyük Patlamadan sonra evrenin oluşumuna ve gelişimine nasıl katkıda bulunduğunu incelenir. Büyük Patlamanın kararlılığını incelemek, kozmik genişlemenin davranışı, ilkel dalgalanmaların evrimi, şişme süreçlerinin varlığı ve kozmik yapıların oluşumu gibi çeşitli olayların araştırılmasını da içerir. Lorentz metrikleri, bu olayları açıklamak için matematiksel bir dil sağlar ve Büyük Patlamanın kararlılığı üzerindeki etkilerin anlaşılmasına zemin hazırlar. Büyük Patlamanın kararlılığı Lorentz metrikleri ve Robertson-Walker modeli çerçevesinde kapsamlı bir şekilde incelenerek, erken evrenin temel doğası ve evrimini şekillendiren süreçler hakkında daha derin bir anlayış elde edilmesine olanak verir. Bu çalışmalar, kozmik yapıların kökenleri, madde ve enerjinin dağılımı ve evrenin geniş zaman aralıklarındaki gelişimi hakkındaki bilgilerimizin artmasına katkı sağlar [14-15].

7. Sonuç ve tartışma

Lorentz uzayı teorik fizikçiler ve matematikçiler için çalışılan kapsamlı bir alandır. Bu alan 20. yüzyılda Einstein'ın özel ve genel görelilik kuramlarının kullanılmasıyla popüler olmuştur. Bu kapsamda Lorentz metrikleri, Einstein denklemlerinde kullanıldığında, uzay-zamanın global özelliklerinin kararlılığı, G-Tekillikler ve ayrıca Büyük Patlamanın kararlılığı hakkında önemli sonuçlara ulaşmamızı sağlar. Bu metrikler, uzay-zamanın geometrisini ve içindeki maddenin davranışını anlamak ve evrenin genel özelliklerini keşfetmek için önemli bir araçtır [16-19].

Teşekkür

Kaynakça

[1] C.W. Misner, K.S. Thorne and J.A. Wheeler, "Gravitation", New Jersey, USA: Princeton University Press, 2017.
[2] S. Hawking and G. Ellis, "The Large-Scale Structure of Space-Time", Cambridge, UK: Cambridge University Press, 1973.
[3] M. P. Hobson, G. P. Efstathiou, A. N. Lasenby, "General Relativity: An Introduction for Physicists", Cambridge University Press, 2006.
[4] B. Schutz, "A First Course in General Relativity", Cambridge UK: Cambridge University Press, 2022.
[5] S. Carroll, "Spacetime and Geometry: An Introduction to General Relativity", Cambridge, UK: University Press, 2019.
[6] D. E. Lerner, "The Space of Lorentz Metrics", Commun. Math. Phys., vol. 32, pp. 19-38, 1973.
[7] C. Nash and S. Sen, "Topology and Geometry for Physicists", Amsterdam, NL: Elsevier, 1988.
[8] G. L. Naber, "Topology, Geometry and Gauge Fields: Foundations", Berlin, DE: Springer, 2012.
[9] J. M. Lee, "Introduction to Smooth Manifolds", Berlin, DE: Springer, 2013.
[10] L. Godinho, J. Natário, "An Introduction to Riemannian Geometry: With Applications to Mechanics and Relativity", Berlin, DE: Springer, 2014.
[11] P. J. E Peebles, "Physical Cosmology", New Jersey, USA: Princeton University Press, 1971.
[12] R. Penrose, "Lectures in Mathematics and Physics", New York, USA: W. A. Benjamin, 1968.
[13] R. P. Geroch, "Article in Relativity", New York, USA: Plenum Press, 1970.
[14] N. Straumann, "General Relativity and Cosmology", Berlin, DE: Springer, 2013.
[15] S. Helgason, "Differential Geometry, Lie Groups, and Symmetric Spaces", Providence, USA: American Mathematical Society, 2001.
[16] A. Zee, "Quantum Field Theory in a Nutshell", New Jersey, USA: Princeton University Press, 2010
[17] L. Ryder, "Introduction to General Relativity", Cambridge, USA: Cambridge University Press 2009.
[18] M. Nakahara, "Geometry, Topology and Physics", Boca Raton, Florida, USA: CRC Press, 2003.

[19] H. Sati and U. Schreiber, "Mathematical Foundations of Quantum Field Theory and Perturbative String Theory", Providence, USA: American Mathematical Society, 2011

Recycling of valuable elements contained in waste lithium ion batteries

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Abstract

Today, fossil fuels that are not renewable are frequently used. Since their use has continued from past years, their reserves have decreased and since they cannot be renewed, renewable and recyclable materials are needed. These renewable and recyclable energy sources are frequently mentioned because they can be used over and over again or are ready for reuse after being used. In this article, Lithium-ion (Li-ion) batteries, which can be recycled, and the recycling stages of these batteries are mentioned since the authors of the article want to work in this field. Lithium-ion batteries (Li-ion) are a type of battery that can be charged and used as an energy storage device. Li-ion batteries are actively used today. The anode material of Li-ion batteries is usually graphite made of carbon. The cathode material is usually metal oxides. The electrolyte material is usually lithium salt in an organic solvent. Lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium manganite (LMO), lithium nickel manganite cobalt oxide (NMC) are Li-ion battery types. Recycling of these types is carried out using pyrometallurgy, hydrometallurgy and mechanical separation methods. In this period when recycling is increasing day by day, this review article on Li-ion batteries is written to help readers in their studies and research.

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1.Introductıon

Energy is indispensable for human life. When we look at today, energy is used in many fields such as health, education, industry. A disruption in energy that will occur also causes disruptions in our lives [1]. In recent years, the focus on sustainable energy sources has been increasing [2]. Sustainable energy sources become inefficient when they are not suitable for use. It is important to store sustainable energy resources in order to use them continuously and efficiently. The storage of energy helps people at this point [3]. Efficient storage of the obtained energy is possible with batteries. The closest battery to today's batteries was launched in 1969 as a lithium sulfur dioxide (Li-S) battery [4]. Then, lithium-polycarbonate monofluoride batteries were available on the market in 1973 and lithium-manganese oxide batteries by 1975 [5]. The modern Li-ion battery was sold by Sony in 1991 [6]. As a result of various developments, Li-ion batteries have become what they are today. Batteries store energy in short energy in the following way: They have two main components consisting of an anode and a cathode. The oxidation reaction occurs at the anode part and the reduction reaction occurs at the cathode part. There are electrode between the anode and the cathode that allow the transport of electrically charged particles. Electrons transported in this way form an electric current [7]. They are widely used due to their characteristics such as long cycle life, specific capacity, energy efficiency, and the ability to be produced according to the area to be applied [8]. Batteries can be divided into groups such as nickel-metal hydride batteries, Li-ion, decoupled redox flow batteries and lead acid batteries. As a result of the acceleration of technology in recent years, Li-ion batteries have become more prominent [9]. Li-ion batteries are available in 4 different types Decoupled among themselves. CCCCLi NMC batteries have good capacity and stability[5]. Lithium cobalt oxide (LCO) batteries are highly suitable for electronic devices and electric vehicles [10]. Lithium Manganese Oxide (LMO) batteries have high thermal stability of the battery [11]. Lithium Iron Phosphate (LFP) batteries come to the fore with their low raw material costs and long-lasting structures [12], [13], [22]–[24], [14]–[21].

The general characteristics of Li-ion batteries include long cycle life, high cell potential and high energy density, usability between -20°C and 60°C, and fast charging[25]. Thanks to all these advantages offered, Li-ion batteries have a wide range of uses, such as electronic devices that we use in everyday life, electric vehicles and in the healthcare sector [26]. The wide area of use is increasing the demand for Li-ion batteries day by day [27]. But as a result of this demand, the number of batteries used is increasing and millions of batteries are thrown away every year [28]. The environmental and economic damage of discarded batteries is increasing every passing year. To produce a battery with 1Wh storage, an average of 110 gCO_2-equivalent greenhouse gases are released into the environment Tue [29]. By ensuring the recycling of batteries, it is estimated that it will bring sales of 23.72 billion dollars by 2030 [30]. In this context, it is important to ensure the recycling of Li-ion batteries. Current research on the recycling of various Li-ion batteries is included in this article [31], [32], [41]–[50], [33], [51]–[53], [34]–[40].

2. The status of lithium-ion batteries

Commercially used lithium ion batteries have charging and discharging characteristics. Lithium provides the entrance to the graphite developed through the anode component (FIG1). Then, from the cathode component in another direction of the battery, lithium ions are released towards the electrolyte part. This is the simplest description of the charging and discharging process of Li-ion batteries [54]. Lithium ion batteries are actively used in electrical household appliances, battery chargers, technological devices, electric vehicles and industry. As a result of the increasing demand for electric vehicles in recent years, interest in lithium-ion batteries has been increasing. Lithium ion batteries provide benefits in terms of recycling and recovery after use, as well as beneficial use for the environment [55].
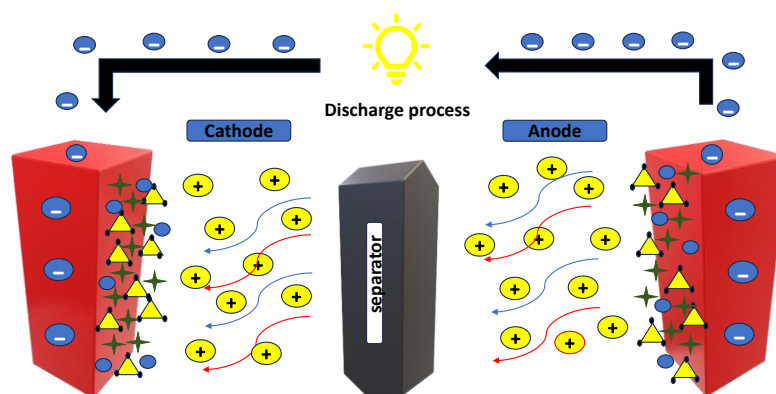
Fig 1. Energy flow diagram of Li-ion batteries from anode to cathode.

Li-ion provinces are preferred more due to the fact that electric vehicles are starting to be used instead of gasoline-powered vehicles. Lithium ion batteries have a positive effect in many ways. Lithium ion batteries greatly reduce greenhouse gas emissions. Lithium ion batteries make the energy collected from renewable energy sources such as wind, solar, geothermal of high quality [56] .

In addition to being successful, lithium-ion batteries also have negative effects in some cases. The production of lithium hydroxide, which leads most lithium electrodes, takes a long time. The start and end period of production of lithium hydroxide material can cover a time envelope of 2 years. The long duration of the production phase causes it to be affected by economic variability and increase the cost[57].

Lithium-ion batteries mainly consist of electrodes, electrolytes and separator components. Anode materials in commercially used batteries are mostly composed of nano-sized graphite. On the other hand, cathode materials may vary depending on the product to be produced [58]. The current state of the most preferred cathodes;

It is known as LCO, LFP, LMO and NMC. Lithium ion batteries manufactured from these different cathodes have different positive and negative properties. If some of these features need to be mentioned;

- Batteries produced from the LO cathode are more expensive and it is observed that O_2 gas comes out in case of overcharging.
- Batteries produced from NMC cathode show slower speed compared to others.
- On the other hand, a negative feature of LFP batteries is that the electrical conductivity condition is low.
- The batteries produced with $LiCoO_2$ have a high-performance electric conduction feature.
- As observed in the current situation, LCO is preferred more when the properties are compared. The most preferred cathode product in the portable electronics sector is $LiCoO_2$ [56].

Various chemical and physical changes such as volume changes, phase transition, side reaction can be observed while lithium ion batteries are in operation. There are complex layouts that Li-ion batteries have realized. These complex layouts show the technique of connecting directly to the electrochemical reaction of a Li-ion battery.

The characterization represents the principle of operation of the batteries and the status of the analyzed studies. In order for the research to be put into practice, the batteries must be fully operational under the conditions required by the defined order. This process often brings with it specially developed devices and measuring devices. When controlled by taking these studies into account, it is seen that the methods of characterizing lithium ion batteries have been developing more rapidly in recent years. In this regard, especially in the studies carried out after the increasing interest in recent years, the projects developed also have an important place in the research [59].

3. Ensuring recycling of used lithium-ion batteries

The recent increase in the use of lithium-ion batteries has resulted in thousands of tons of battery waste [60]. Recious metals are used in the production of these batteries. In this context, it is obvious that the recycling of precious metals in used batteries is of great importance. Recently, as can be seen in Graph 1, when we look at the studies with the words "lithium-ion batteries" and "recycling"; it is seen that there were 3 articles in 2012 and 149 articles in 2022. This situation also emphasized the importance given to recycling.
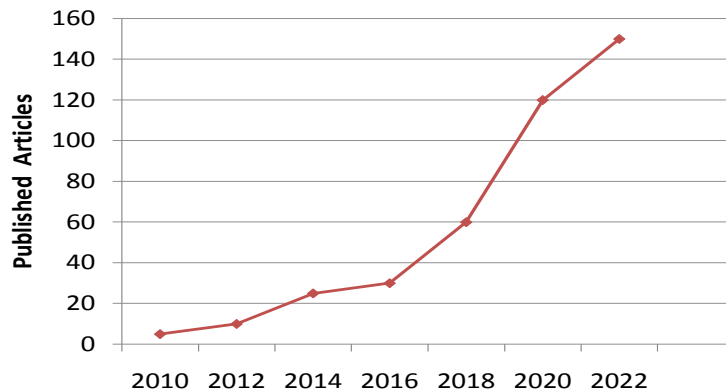
Fig 2. Distribution of articles written about Li-ion batteries by year.

In addition, with this increase in the number of articles, it is seen that it makes a high contribution to the recovery of valuable and scarce resources in the world in order to ensure a sustainable future [61], [62]. In this context, it is known that many different methods are used in recycling studies. Mechanical, pyrometallurgical and hydrometallurgical methods can be given as examples[63].

3.1. Recuperation of cathode substances from discarded LCO batteries

Lithium cobalt oxide (LCO) is the first cathode material to be released to the market. For more than 30 years, the market has been widely used. LCO batteries have become a popular energy source with the increase of electronic devices and electric vehicles [64]. Research shows that by 2025, the need for LCO batteries and the raw materials to make them will increase [65]. Considering the developing and growing Sunday, recycling of LCO batteries that have become unusable is of great importance when considering their macroeconomic and environmental impacts [66]. Recycling of LCO batteries can be achieved by various techniques: chemical categorization can be achieved by direct regeneration, pyro metallurgical, hydrometallurgical techniques.

3.1.1. Recycling processes by hydromealgic technique

Hydrometallurgical recycling technique can be characterized as the place where various leaching(leaching=precipitation and calcination processes are performed [67]) it includes transactions. Precious metals are obtained with chemicals that do not show solvent properties in the leaching process. Organic acids are preferred in leaching processes today. Organic acids are used in the internal processes of LCO. Qu et al., for instance, leached the LCO cathode material following high-energy ball milling using 1.25 M citric acid [68]. When the experimental results were examined, it was shown that the optimum leaching process of 94.91% for

cobalt (Co) and 97.22% for lithium (Li) was realized with the optimum grinding speed of 500 rpm and the optimum experimental condition of 80°C in 30 minutes. In another example, it was performed by Chaudhary and others [69].1.25 M citric acid and 1% H_2O_2 were combined by Chaudhary et al., for the leaching procedure. He finished the leaching process at 90 °C in 5 hours. At the end of the process, the yield was found to be 99.93% for cobalt and 99.7% for lithium.

In another study, Verma Et al., [70] LCO leaching was performed using 0.58 Moxalic acid ($H_2C_2O_4$) and 1.16 M hydrogen peroxide (H_2O_2). It has been shown that the mixing speed is realized with an optimum experimental condition of 600 rpm and a temperature at 80°C. After that, KOH was added to raise the pH, causing it to rise over 13. Lithium was precipitated with potassium carbonate (K_2CO_3) and Li_2CO_3 was released. Then, for the recovery of cobalt, $CoC_2O_4•2H_2O$ was gradually added. KOH has been added because it is necessary to keep the pH high. Weak Co yield has been observed.

Liao Et al., tried a different approach. Biolic process it has managed to separate 99% of Co, and 100% of Li from batteries that have become unusable with [71]. A mixed culture containing *Acidithiobacilluscaldus* and *Sulfabacillus* thermos sulfidooxydans was formed during the biolic process. Lossless removal of metals from "Stemphyliumleafblight" (SLB) has been facilitated by Fe $^{2+}$ -MCB process. For this reason, the harmful SLB has become harmless and has lost its toxic effect. Deep eutectic solvents (DEC) are often preferred in analytical chemistry applications today. DECs are an alternative to ionic plasters. They exist in liquid form, such as ionic liquids, at room temperature. When combined with different solvents, it provides low vapor pressure and is economical. According to Peters et al., using DEC. Co and Li have managed to decompose from the locos that have become unusable [72]. It is also produced with choline chloride and ethylene glycol. Next, a 10 mL glass bottle was filled with 100 mg of LCO and 5 ml of liquid ant to begin the leaching process. It was mixed for 24 hours at 900 rpm between 180°C-140°C degree and leaching process was performed. The optimum leaching yield was found to be 91.6% at 180 °C at 900 rpm under 24-hour conditions.

Peters et al., showed different approach to DEC and proposed an economical and environmentally friendly solvent with choline chloride-citric acid solvent [73]. The study provided evidence that, in the presence of copper and metallic aluminum in LCOS, a 2:1 M solution of citric acid and choline chloride diluted with distilled water is an effective solvent. With this method, LICoO2 was filtered at 40 °C and 60 minutes and >98% of cobalt (II) was separated.

Liu et al, tried a low-cost DEF approach and achieved Li and Coextraction efficiency close to 100% [74]. They used microwave to separate Co and Li from LCO. In the scope of the study; DEF was used for leaching in microwave, low viscosity and low temperature. The mixture was mixed at 80°C for 30 minutes until it became homogeneous. Then he glided away. Saturated sodium carbonate solution was added and Co recovery was realized. The filter process has been applied and dried.

3.2. Recovering cathode material from LFP batteries that have become empty

LFP batteries are a type of battery that is mostly used in electric vehicles and smart systems [75]. Especially the interest and increase in electric vehicles has also increased the interest in LFP batteries[76].The increase in the use of LFP batteries has led to an increase in the number of waste batteries [77].Waste LFP batteries must be disposed of carefully. The most valuable component of expired LFP batteries is lithium [78]. Due to the distinctive feature of LFP crystals, the Li component can be selectively removed using engineering techniques. Li extraction has aided in the advancement of several useful technologies, including electrochemistry, pyrometallurgy, hydrometallurgy, and mechanochemistry [79].

3.2.1. Hydrometallurgical technical recycling processes of LFP battery

The recycling stages of LFP batteries by applying hydrometallurgical processes can be found in the relevant sources [38],[81]. To give an example of these recycling steps; Fan et al. during the work he did, the battery was charged and the supply of iron (III) phosphate (FePO4) and lithium graphite, which will be used to extract lithium, was provided Jul[82]. He first used water as a leaching material [67]. The removal of lithium from the anode is given in the following equation (reaction 1). In the second and third equations, the equation created with the NaOH cathode for the recovery of iron and phosphorus is stated [82] (reactions 2-3).

$$2LiCx + 2H_2O \rightarrow 2LiOH(aq) + 2xC + H_2 \tag{1}$$
$$FePO_4 + 3NaOH(aq) \rightarrow Na_3PO_4(aq) + Fe(OH)_3 \tag{2}$$

$$Na_3PO_4(aq) + 2LiOH(aq) \rightarrow 3NaOH(aq) + Li_3PO_4 \tag{3}$$

The Na_3PO_4 solution was mixed with LiOH solution. As a result of this mixture, lithium phosphate was formed. For this reason, NaOH was formed again and a loop was created to filter it again. Three parameters were used in this study. These parameters are the volume of the substance of the filter, the concentration of the substance of the filter and the filtration time. In the study, suitable leaching conditions were determined as 0.5 hours, sodium hydroxide (NaOH)/Fe molar fraction of 4.5 and 1 mol/L NaOH, and the appropriate leaching yield was determined as 99.7%. It has been observed that the method used with the help of these efficiency values is better and more suitable than the traditional pyrometallurgical and hydrometallurgical methods. Removing the components used as an anode or cathode from the LFP battery determines the flow contact. Removing the components used as an anode or cathode from the LFP battery determines the flow contact (Figure 2) [56].
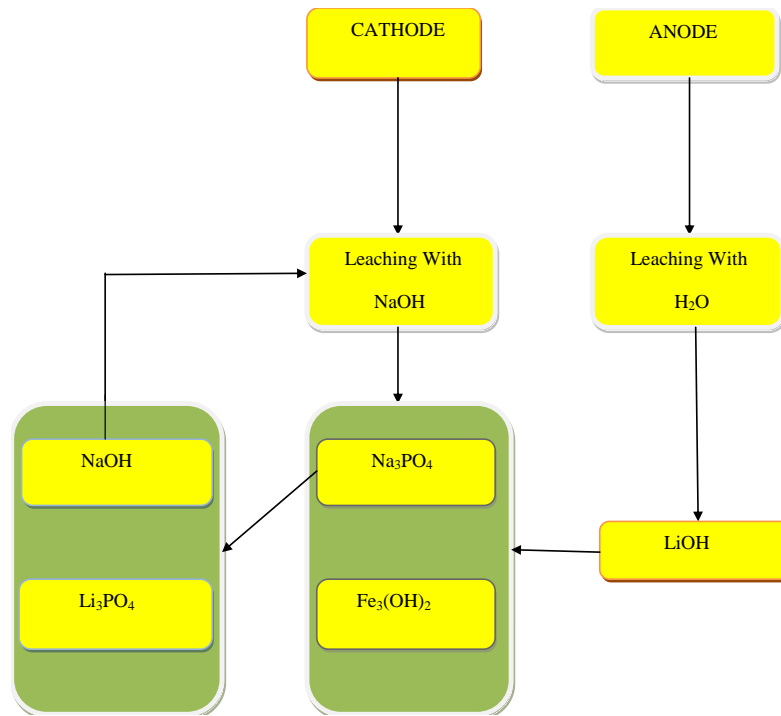
Fig 3. Flow diagram of removing components used as anode or cathode from an LFP battery.

Liu et al.'s study claims that certain mechanisms involving sodium hypochlorite (NaCIO), hydrochloric acid (HCl), an acidic environment, and oxidants caused reactions to occur in reconstituted LFP batteries [83]. In this context; HCl/Limolar ratio, HCl concentration and CIO/Li ratios were investigated. The results of this study indicated that the most suitable operating parameters for the internal efficiency of Li were; T= 15 °C; HCl - LLI molar ratio= 1.3; NACIO - NUNLI ratio= 0.6; t=5 min. In addition, Li-ions contained in the leaching solution for the extraction of Li_2CO_3 were precipitated with the help of Na_2CO_3 (sodium carbonate). In addition, the leaching residues produced from $FePO_4$ can be used for the regeneration of LFP powders. This process allows the separation of metal ions, which are difficult to separate, and as a result of the leaching process, Li_2CO_3 and $FePO_4$ were obtained [83].

Yue et al. in his study, it is possible to recycle LFP batteries with visible light photo decay ($NaFeS_2$) produced in addition to the recovery of Li and P [50],[52]. First, LFP powder was added to sodium peroxidisulfate ($Na_2S_2O_8$) solution, then it was mixed for 30 minutes. As a result of the processes performed to obtain LFP powder, the Li ion was recovered. After these steps, it reacted with LFP and Na_2SO_8 at room temperature. This reaction produced a photocatalyst ($NaFeS_2$) and phosphorus was formed [87].

The appropriate parameters are listed as LFP/Na_2S= 1; LFP/Na_2SO_8= 1:0.9; reaction temperature= 24°C; mixing time= 30 minutes. The ability of $NaFeS_2$ on absorption and photocatalytic synergistic has been tested. The results were then compared with methylene blue (MB)and TiO_2. As a result of the comparison, it was determined that MB was 67 times faster than TiO_2 when the degradation rate of methylene blue and TiO_2 by $NaFeS_2$ was compared. Thus, it has been revealed that the synthesized $NAFeS_2$ is suitable for removing organic paint pollution [88].

3.2.2. Recycling processes of LFP battery by pyrometallurgical technique

One kind of extractive metallurgy that is particularly useful for removing and recovering metals from materials is pyrometallurgy [82].This method can show processes such as concentrating, roasting, simplified recycling process and high temperature melting technique. Although this method provides important advantages such as high processing capacity and high applicability, it shows high energy consumption [89],[81].

In pyrometallurgy, research is done on recycling LFP batteries using techniques such sodium salt aided roasting. Zhang and associates carried out a study with two distinct sodium salts. Na_2CO_3 and naoh are these salt kinds [90].The carbothermal reduction approach is another one of these investigations. Using this method, a spent Li_2CO_3 battery was converted into the same product using an LFP battery. The following is the response for obtaining Li_2CO_3 again [56] (reaction 4 and 5).

$$2LiFePO_4 + (NH_4)_2S_2O_8 \rightarrow 2FePO_4 + Li_2SO_4 + (NH_4)_2SO_4 \tag{4}$$
$$Li_2SO_4 + Na_2CO_3 \rightarrow Li_2CO_3 + Na_2SO_4 \tag{5}$$
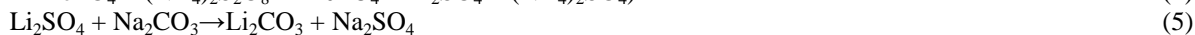
3.2.3. Recycling processes of lfp battery by mechanochemical technique

The mechanochemical method is a method used to extract Li from the LFP battery [91], [92] In this method, sodium citrate is a common grinding agent that does not contain pollution and provides recovery. After mixing the LFP powder with sodium citrate, it was mixed with hydrogen peroxide. Then, the zirconia was placed in a grinding jar with a bal. 98.9% of t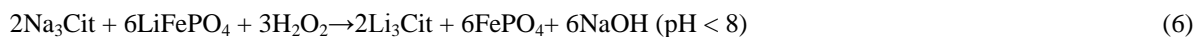he Li obtained from LFP is selectively usable, and the remaining Li is converted to Li_3CIT and dissolved in water. Under favorable conditions; Sodium citrate/LFP mass ratio 10: 1; addition of 1mL H_2O_2; 500 rpm rotation speed and milling time in 5 hours; Reactions of this process (reactions 6 and 7) [92];

$$2Na_3Cit + 6LiFePO_4 + 3H_2O_2 \rightarrow 2Li_3Cit + 6FePO_4 + 6NaOH \ (pH < 8) \tag{6}$$
$$FePO_4 + 3NaOH \rightarrow Fe(OH)_3 + Na_3PO_4 \ (pH > 8) \tag{7}$$

3.2.4. Direct regeneration processes

LFP recycling can be performed with the direct regeneration technique. The used LFPs become reusable with a functionalized pre-separation separator and electrochemical treatment of the electrode.
The regeneration process was carried out to reconstruct the cathode particle structure, which had undergone decay, without damaging the bulk phase [93], [94].
Pre-lithification of the pre-separation separator started with the electrochemical deposition of a thin layer of Li-rich material on a commercial separator [95]. In this context, the reason why lithium oxalate (LiC_2O_4) is chosen for the transportation of Li is its air stability and low cost.

3.2.5. Recycling processes by electrometallurgical technique

Lithium is extracted from salt water by using lithium iron phosphate ($LiFePO_4$) cathode materials. Salt lake water and Li minerals are the primary sources for lithium products [96]. The high concentration of Li in the brine obtained from the Salt Lake provides cheap extraction costs. For this reason, Li extraction from salt water is one of the most preferred options. Characteristically, salt water variably has the elements Li, K, Ca, Na and Mg. Electrochemical extraction method methodology (ELEM) has been developed to provide Li extraction from salt water [97]. This method is environmentally friendly, easy to use and does not need additional chemical reagents. Thanks to these features, it is more advantageous than traditional extraction methods [98].

3.3. Recovering cathode substances from LMO batteries that have become empty

Due to the scarcity of minerals to be used for battery production and the high cost of processing, it is very important to recover these minerals from used batteries. Li-ion batteries used to store energy today have short lifetimes. Sustainable recycling methods of these batteries have been one of the most focused topics in recent years [99].Recycling plays an important role in the sustainability of Li-ion battery production, as it reduces the demand for virgin material and the environmental pollution caused by irresponsibly disposed batteries [100].

Lithium manganate ($LiMn_2O_4$) batteries are more advantageous than lithium cobalt (LiCo) batteries. LMOs have a preferred cathode material due to its high operating voltage, low cost, low toxicity, high reserve, reliable by nature and environmentally friendly [101].

Some used Li-ion do not contain a single cathode material. Due to this, differences may be observed in recycling methods. Various methods are used for the recovery of cathode materials of intact lithium manganese oxide (LMO) batteries [56],[102].

3.3.1. Recycling processes of LMO battery by hydrometallurgical technique

The hydrometallurgical process is the first method for the Li-ion battery to be recovered [102].It involves the leaching and separation of metals in an aqueous environment. The process steps consist of acid/alkali leaching or bio-leaching, chemical deposition, solvent extraction and electrochemical deposition [103]. Leaching systems are made with inorganic acids such as HCl (hydrochloric acid), H_2SO_4(sulfuric acid) and HNO_3(nitric acid). In addition, although it has been tried to be used in H_3PO_4 (phosphoric acid) and organic acids, H_2SO_4 has been preferred due to its prices and reactivity [104].

Wu Et al., renewed the spent $LiMn_2O_4$ battery by chemical reduction method, the Li source of which was lithiatedpyrene (Pyrene- Li), using the hydrometallurgical process. The Pyrene-Li compound is a reagent that can give electrons (e-) and Li^+ and has a high amount of reducing agents. In this experiment, it was preferred to eliminate the Li deficiency in the waste LMO cathode. It has been concluded that Li-deficient LMO and degraded LMO prepared by acid deletion method are originally recoverable due to long-term stability and superior speed capacity, which can be compared with intact LMO cathode [105]. In another example, Wang et al., chose to use acid leaching to recover LMO. In this experiment, Wang et al. combined acid leaching with the resynthesis of cathode material. Here, Li and Mn leaching yields of over 94% were achieved using 60 g/L solid-liquid ratio, 1.0 M citric acid, and 1 h leaching. Spinel LMO was resynthesized by sol-gel method using the leachate generated after leaching[106].The studies carried out were not limited to these two experiments.

In another example, Zhou et al. succeeded in recycling $LiMnO_{24}$ cathodes without using acids, bases or chemical reductants, only a pH gradient provided by neutral water electrolysis [107]. Mohanty et al. used Na-D_2EHPA as an extractant and sulfuric acid as a decomposer. They investigated the recovery of MN from used oil using hydrometallurgical process [108].Yao et al. tried to recover LMO both inexpensively and in the most environmentally sound way. For this purpose, they used citric acid as leaching reagent and glucose as reducing agent [109].

3.3.2. Recycling process of LMO battery by pyrometallurgical technique

In the pyrometallurgical process, non-metallic components are decomposed into gas. Metallic components, on the other hand, reduce the spent Li-ion in a high-temperature furnace, where they are reduced to alloys or metals. But there are negative aspects such as high energy consumption, the product formed as a result of the process is not pure enough, the release of secondary polluting gases such as dioxin, furan [110]. Looking at the studies conducted; Tao and colleagues have pioneered studies on the recovery of $LiMn_2O_4$ batteries with one-step pyrolysis that does not contain acid leaching as a reductant. After, LMO powder was placed in the quartz tube and electrolyte evaporation was demonstrated between 30-180°C in the first stage. In the second stage, high temperatures (180-800°C) were reached and CO_2 emission was observed while the cathode material was reduced. It has been observed that manganese (LMO), which has a high valence, is reduced to 500 °CMNO. The leaching efficiency of Li at 1 hour pyrolysis time with a nitrogen flow rate of 50mL/min at 500°C has been calculated as 99% and the leaching efficiency of manganese is 99.4% [111].

Liu et al stated that water and sulfate purification leaching methods can be used to recover Mn and Li from LMO. $NaHSO_4$.LMO powder combined with H_2O is roasted between 308-773°C. The Li element in the sample, which was subjected to roasting at a temperature of 600°C and for 30 minutes, was taken back as $LiNaSO_4$. A

change in the valence of the Mn element has been observed. This change has been observed from +4 to +2. After the roasting process, water leaching conditions were applied and the electrification rate of Li was found to be 96.6% and the extraction rate of Mn was found to be 9.7% [112]. Liu LMO has not been limited to investigating the recovery of batteries by the pyrometallurgical process only with this experiment and has investigated the low-cost and environmentally friendly recovery of LMOs using NMP (N-methyl-2-pyrrolidone) in another experiment [101].

Han et al. colleagues investigated the effects of roasting temperature and duration on surface modifications by using the roasting-assisted flotation method from LMO batteries. It has been observed that $LiMn_2O_4$, which was subjected to flotation after the roasting process, was easily separated from graphite. Other analyses have shown that the main reason for the difficulty in separating $LiMn_2O_4$ from graphite is due to the organic binder and electrolyte coating on its surfaces. As a result of this experiment, it was observed that the effects of organic films decreased by changing the contact angles through roasting [113].

Studies of Li and Mn recovery from LMO cathode spent by He et al. method of salt roasting at low temperature [114], Pindar et al. recovered manganese and Li from coin cells by heat treatment using organic acid leaching [115] these are the other studies that we come across in the literature for pyrometallurgy. Hydrometallurgy and pyrometallurgy can be used separately or combined [116]. It is a method that has made its name in the combined pyro-hydrometallurgical process in recent years. This method, which has emerged in accordance with the principles of green chemistry, starts with a thermal pretreatment step involving the collection of cathode materials. Then it continues with the unified recovery process of cathode materials. As the last step, the subsequent separation and extraction process is also carried out [117].

3.3.3. Recycling processes of LMO battery by electrochemical technique

Liang et al. the parameters of recycling manganese element from LMO battery were determined by electrochemical method. These parameters: graphite rod for the counter electrode, a working electrode coated with LMO powder, and finally Ag/AgCl electrode (reference). As a two-electrode system, a constant voltage deoxidation process was determined by using graphite clasp as the cathode and graphite plate as the anode. After these procedures, the temperature of electro-oxidation at a voltage of 0.5–3.0 V was set at 750 °C, and the reduction process of LMO was observed for 12 h. In this experiment, Li could be recovered to the desired extent, while Mn could not be recovered at the desired level. As a result of these experiments, it can be said that the hydrometallurgical process, which is both low cost and environmentally friendly, is more usable for the recovery of Mn and Li [118][56].

3.4. Cathode material recovery from used NMC batteries

Lithium nickel manganese cobalt oxide ($LiNi_xM_{ny}Co_zO_2$,NMC), one of the important materials in batteries, has high energy density[119]. Thanks to its layer-shaped structure, it changes its volume at a rate of 2% [120]. Promising Li-ion batteries for the future make up the cathode material group [121]. During the addition and removal process, the Li content can reach up to 20%, providing electrochemical stability. NMC provides affordable cost thanks to its high capacity and Mn [122]. The three NMC batteries have chemically similar properties. For this reason, selective and efficient recycling of used NMC batteries has become a difficult goal. When new NMC batteries are produced from used NMC batteries, selectivity is a less important feature in recycling. The separation of cathode materials from used NMC batteries is usually carried out in recycling plants.

The recovery process allows the precious metals contained in the batteries to be separated and made reusable. This process reduces environmental impacts and also reveals an economical method because it produces less electricity [123]. Three main processes are needed to recycle NMC batteries: Hydrometallurgical, pyrometallurgical and mechanical [124].

3.4.1. Recycling processes of NMC battery by hydromealgic technique

The hydrometallurgical process involves reactions that take place in the liquid phase. It mostly involves obtaining the desired precious metals as a result of the decomposition of a metal in the form of a special. In cases where it is difficult to separate some metal ores by other methods, the hydrometallurgical method is used. These processes are carried out by purification methods such as precipitation, liquid-liquid extraction, adsorption, ion

exchange after the leaching process [125]. Hydrometallurgical processes provide the recovery of a larger amount of metal compared to pyrometallurgical processes. Ilyas and others [126] in a study conducted by, it is a recovery method that occurs with the precipitation of Li_2CO_3, which occurs as a result of filtering Li at 90 ℃ for the used NMC cathode and adding Na_2CO_3 at the ideal dose of $Li+: CO_{2-}=1:1.5$ Li_2CO_3. After that, the cathode material was leached at 90 °C for about 3 hours using a 3 M HCl solution. As a result of this process step, the dissolution of Co, Mn and Ni was achieved with an efficiency of over 99%. Then, at Mn 80℃ in the leachate, $KMnO_4$ was added at a stoichiometric ratio of 1:1.25 with a pH of 2.0, resulting in selective precipitation. Furthermore, Co and Ni pH were extracted from leachate using an ionic liquid (organic: aqueous) with a ratio of 5.4 and 2:3. Two milliliters of 2 M H_2SO_4 solution were used to carry out the ionic liquid's breakdown. Co_SO_4 with high purity has been degraded via evaporation. It created the crystals of xH_2O. At 50 °C, Ni ions precipitated as $[NiCO_3·2Ni(OH)_2]$ with a pH of 10.8, and a stoichiometric ratio of $Ni_2+: CO_{2-}= 1:2.5$.

Wang et al., in a study he conducted, calcination process was applied to aluminum foil in a CO_2 atmosphere at 600 °C for 2 hours [127]. As a result, the aluminum foil is separated from the cathode strips of used Li-ion batteries. The slag obtained after calcination is stripped from the aluminum foil. The goal was to get a solution that contained Mn^{2+}, Ni^{2+}, Co^{2+}ions. For this purpose, it was diluted with 1.5 M HCI for 2 hours at a rate of 20 g/L (solid: liquid). The aluminum foil, which was recovered after separation from the cathode strips, was used to obtain Ni-Co-Mn nano-sized powders from the leachate. Aluminum foil served as a reducing agent here, replacing Ni^{2+}, Co^{2+} and Mn^{2+} ions. In this way, a low-cost agent was used with aluminum foil. In addition, the reduction of waste has been ensured. The recovery yields of Ni, Li, Mn and Co in this method can be listed as 97.5%, 94.05, 4% and 99.3%.

According to Li et al.'s research, NMC cathode powder was leached for 60 minutes, using a 2.5 M H_2SO_4 solution, at 50 °C that contained 5% H_2O_2 at a rate of 25 mL/g (liquid: solid) [128]. The internal yields of Ni, Co, Li and Mn were found to be 97.20%, 99.12%,99.54%, and 99.23%, respectively, following the leaching procedure. Following the addition of dimethylglyoxime (DMG) to the solution, nickel ions precipitated as Ni-$(C_4H_8N_2O_2)_2$ with a 99.35% yield. Subsequently, Co and Mn were extracted with yields of 99.95% and 99.35%, respectively. For the extraction of Co, a solvent consisting of 10% C272 by volume was used at a ratio of 1:1 (O/A) at pH 6. For the extraction of Mn, a P_2O_4 solvent of 10% by volume was used for 10 minutes at a pH of 3.5 in a 3:1 (O/A) ratio. The last step is to remove the metal ions loaded into the organic phase with a dilute H_2SO_4 solution. MnO_2, Li_2CO_3 and CoC_2O_4 have been recovered in the form of. As a result of all the process steps, the extraction yields for Ni, Mn, Li, Co were defined as 96.84%, 92.65%, 91.39% and 81.46% respectively.

In a study by Xuan et al., presented a method to recover the utility of the NMC111 cathode using antisolvent precipitation [128]. [129]. The filtration step was performed with 1.5 M citric acid at 20 g/L (solid) at 50℃. Non-solvent ethanol, acetone, etc. with the addition of dissolved metal ions turn into citrate form and precipitation process is performed at 25 ° C. Precipitation of Li has not been achieved. For this reason, the separation of Li has taken place. Then, acetone was added to the leaching solution in a ratio of 2:1. The recovery yields can be listed as 97.0% Co, 86.9% Ni and 99.7% Mn. The final stage involved calcining the collected sediments at 900 °C and 50 mL/min of oxygen. The outcome of this process was a mixed metal oxide product.

In the part to be explained, deep eutectic solvents (DES) were used. Deep eutectic solvents have high dissolving capacity. Melting points are low. It is also known that it can dissolve different metal oxides. Deep eutectic solvents are also known and used as green solvent in the separation and recovery of metals [129]. Liquid form is accessible at temperatures ranging from ambient temperature to 70℃. Because of this, it functions as a leaching agent in the hydrometallurgical process' leaching step [130]. It works well for the sustainable and ecologically friendly recycling of used Li-ion batteries.

Luo et al. in his research, deep eutectic solvents based on choline chloride (CHCl) and oxalic acid were used for the recovery of used NMC523 [131]. The precious metals in the NMC523 cathode have completed the filtration process in 20 minutes and at 110℃. Researchers have suggested that filtration systems can be used that allow Li-ions to be selected from water.

Ma et al. in a study he conducted, a deep eutectic solvent based on tartaric acid and choline chloride (TA/CHCl) was employed to extract the spent NMC cathode [87]. An antisolvent crystallization approach was applied to the leachate by adding ethyl alcohol. The deep eutectic solvent used was leached at a temperature of 70 ℃ and within a short period of time. Thanks to antisolvent crystallization, the precipitation efficiency was realized at a rate of 98.5% for Ni, Co, Mn. The precipitate released because of antisolvent crystallization provided the recovery of DES and antisolvent and was proposed as the starting point for a new cathode.

3.4.2. Recycling processes of NMC battery with pyrometallurgy technique

Pyrometallurgical processes take place because of high temperature reactions. After heat treatment is applied to metal ores, it aims at the recovery of precious metals [132]. As a result of heat treatments, the material undergoes chemical and physical changes. Applications such as drying, calcination, roasting, refining are included in the pyrometallurgical process [133]. The high cost of pyrometallurgical processes and the fact that they are not environmentally friendly due to the gases released during combustion events are considered among the disadvantages of this process.

To recover Li from a used NMC battery, Zhang et al. there is a research that he has done [134]. In the research conducted, it has been proposed to perform a carbothermal reduction process in addition to the multi-step leaching process. Based on the acquired data, NMC was reduced to CoO, Co, Ni, Li_2CO_3, NiO, and $LiAlO_2$ following the reduction process. Li's recuperation was accomplished in three stages. Water leaching was used to first recover the Li salts that were soluble in water. This process's efficiency was found to be 73.80%. Li was subsequently extracted from Li-Al compounds using the alkaline leaching technique. This technique has been shown to have an efficiency of 13.86%. The process of adjusting pH is the final step. Li, which collapses together with aluminum during pH adjustment, has been recovered by roasting process together with water leaching. The efficiency of this process has been determined as 96.3%. The recovery of Li from the NMC cathodes used with a multi-step approach has been achieved with a total extraction efficiency of 87.15%.

A pyrometallurgical approach has been adopted by Yan et al. for the recovery of Li from used NMC batteries [135]. Mn persisted as an oxide at temperatures below 800 ℃. Metal has been reduced to Co and Ni. Mn persisted as an oxide at temperatures below 800 ℃. Metal has been reduced to Co and Ni. It has been transformed into the forms of Li, Li_2CO_3 and Li_2O at temperatures higher than 900 ℃. Li was extracted using a water leaching procedure for 30 minutes at a rate of 5 mL/g (liquid: solid), yielding lithium hydroxide and carbonate. It has been established that this method has a 93% efficiency. Furthermore, the impact of contaminants on Li's recovery rate was examined in this investigation. By using the lithium aluminate synthesis process, it has been found that the Li recovery rate drops in the presence of Al and that Cu has no discernible influence.

Hydrogen gas can be used as a reducing agent. This method is a non-harmful alternative for the environment used in the recovery of precious metals. It does not require the use of a dangerous chemical.

Bhandari and Dhawan's in their study, the recovery of metals from waste NMC powder was achieved thanks to the reduction of hydrogen. Li salts (LiOH, Li_2CO_3) were recovered in 60 minutes and at 500 ℃. Selective recovery was obtained with 91% and 63% efficiency using pure H_2 and 10% H_2+90% Ar. The two methods used to achieve decontamination were pure H_2 and 10% H_2 + 90% Ar. Bhandari and Dhawan observed that the amount of Li recovered is decreased by the FIBER salt that is emitted during Li recovery. They declared that the PVDF ought to be eliminated. Following the removal of PVDF, the H_2 gas's reduction efficiency rose, and in an hour at 500°C, the recovery of Li increased from 63% to 91% [136].

3.4.3. Recycling processes of NMC battery with mechanochemistry technique

Liang et al., have tried a new mechanochemically supported way to recycle the cathode materials used. The cathode material used in this experiment was ground with ammonium persulfate $((NH_4)_2S_2O_4)$ and sucrose in an iron grinding bowl. Then the cathode material obtained was leached. The leaching yields were found to be 97.1%, 94.0%, 87.6% and 93.8% respectively for Li, Ni, Co and Mn. Although this experiment is innovative, recovery processes are required in metals subjected to leaching [137].

Cuhadar et al. they used magnetic separation and buoyancy techniques to remove plastics and precious metals from waste MNC cathodes, and reverse buoyancy technique to separate plastics. Then, the remaining black substance was filtered for two hours at 60 ° C using 2M H_2SO_4 solution at a dosage of 40 g / LH_2O_2. The leach yields for Co, Ni, Mn and Li are respectively %96, %94, %95, %98 it was found as [138].

Qiu et al., he used pretreatment and flotation techniques for the separation of graphite and NMC found in waste LIB. The effect of pretreatment processes on the flotation process has been investigated. The preliminary processes start with 0.5 M Fenton reagent. Roasting is performed at 450 °C for 30 minutes. Under optimal conditions, the efficiency of NMC cathode active materials and graphite was found to be 90% and 75%, respectively [139].

Liu et al. he preferred the process of grinding the Li-ion found in the waste state at low temperature. The low temperature properties of the binder have been investigated. Examining the experimental data, it was found that

the electrode plates exhibited great selectivity when manufactured at a low temperature for five minutes as opposed to grinding at room temperature. [140].

4. Prospects for battery recycling in the future

With the increase in population in the world, existing resources are being depleted day by day. It is becoming even more important to use existing resources more effectively and more efficiently [56]. Apart from increasing energy demands, the population growth in the world, together with the changing lifestyle and the fossil fuel resources that are about to be depleted, leads to dependence on renewable energy sources [141]. Considering environmental and socioeconomic concerns, extensive studies have been conducted in the literature to examine the use of alternative fuels, especially in the transportation sector, and lower carbon fuels [142].Since their invention in the 1970s, Li-ion batteries have gained significance in the market for portable electronic devices because of their special qualities, which include a high energy capacity and a long service life. In contrast to other battery types (such NiMH and Pb-acid), LIBS provide less of a harm to the environment. Its lifespan is extended. It is well-designed and better resistance against self-discharges is provided by it. It offers greater output voltage and resistance to high temperatures [143]. Li-ion batteries with these superior properties will be widely used in the production of electric vehicles today and in the future. At this point, the need and demand for minerals in the production of these vehicles and also in battery storage technologies is important. In this context, Li metal in particular is expected to be used 40 times more than cobalt, nickel and graphite [141]. There is a significant gap in the production and recycling of Li-ion battery. Globally, less than 5% of Li-ion are recycled, while in India alone, more than 50,000 tons of Li-ion waste are produced annually. Some non-recycled batteries are used in second-life applications such as energy storage systems [144]. Recent patents show that waste batteries offer high potential for profitable recycling. In the study of Wang et al., it was stated that pyrolysis achieved an electrolyte removal efficiency of almost 100% [56].   However, it will also release a lot of dust and harmful fumes that include fluorine and organic materials that need to be treated. Another method for handling used electrolyte is solvent extraction. Currently, there are two types of solvent extraction, which are used to process the used electrolyte. The first is organic solvent extraction. To be used in the production of new batteries; A technique has been developed to recover Ni, Mn, Co, and Al metals from Li-ion batteries. At this point, it became possible to reuse the cathode active material following thermochemical reactions. Tran et all,. ın a study conducted by; Regarding this issue, they suggested converting Li-ion batteries using green chemicals and technologies. With their study, they showed that high extraction efficiency can be achieved with an environmentally green method using deep eutectic solvents at low temperatures[56].

4.1.Recovery of Li-ion battery anode materials and electrolytes

4.1.1. Electrolyte recovery

In a Li-ion battery, the electrical insulation between the decoupled electrodes is shielded by an ion-permeable membrane. An effective ionic conductor can also be an electrolyte. Lithium hexafluorophosphate, which dissolves in carbonate solvents, has been stated to be the best electrolyte for Li-ion batteries[56]. There is a significant degree of fluctuation in the conversion rates reported in the literature; although there is a lot of variability from one region to another, there are still low rates. As an example, Call2Recycle, the organization responsible for collecting Li-ion used in Canada, reported that less than 200 tons of Li-ion battery were collected in 2017. Gies et al., while this amount corresponds to a collection rate of 25%, it is believed that their assessment is an overestimate when considering the sales volumes of electronic and electric vehicles (EV) [56]. Wang et al. based on statistics on the sale of electronic devices as a destination markup, the recycling rate in North America is estimated to be lower than 10% in 2012. To look at another comparison, the collection rate observed in Europe in 2016 by Eucobat was reported to be slightly higher than 15% [105]. Based on these data and the inability of existing pyrometallurgical processes to recover Li, it is estimated that there is a much lower rate of recycling Li from spent Li-ion battery than 1%, which clearly does not comply with the principles of sustainable development. For this reason, it has become mandatory to increase both the collection and recycling rates of Li-ion battery [143].

4.1.2.Recovery of anode materials

To get rid of spent lithium and use it more in new Li-ion batteries, it needs to be more economical and sustainable. Redeployment is not just an anode in libs (lithium-ion batteries), it is more than that. It has also been said that the recovery of graphite holds great promise for use in the fields of supercapacitors, catalysis and water treatment. In addition, the recycling of graphite from waste Li-ion batteries will also have a great impact on the protection of the environment. In light of all this, one of the most interesting transformations in recent years has been the recycling of waste [143].Water infiltration has been demonstrated to be a successful technique for extracting graphite from anode components in a spent Li-ion battery by Bhar and associates. In this instance, an organic solvent based on dimethyl carbonate was used to first wash the recovered graphite. After that, the graphitization time was extended and the intermediate phase of leftover carbon black and white electrolyte that had formed as a result of electrolyte on the graphite surface decay was removed by post-treatment at 750 °C[145].

5. Conclusion

The reasons for the selection of these materials are that the materials used in battery production are considered as strategic raw materials and the use of batteries has increased and therefore the rate of waste batteries has also increased. In addition, the cost of battery production has decreased considerably due to the increased use of batteries. While the cost of Li-ion battery production was 1183 dollars per kilowatt in 2010, this value decreased to 137 dollars in 2020.

Waste has become a big problem today. Therefore, recycling is of great importance. In this article, the recycling of Li-ion batteries, which have been frequently mentioned in recent years, is discussed. Procedures and techniques used in the recycling of Li-ion battery types including LFP, LCO, NMC and LMO batteries are discussed. These methods are categorized under 3 headings: hydrometallurgy, pyrometallurgy and mechanics. Efficiencies to be obtained from recycling in these methods are mentioned.

It is aimed that this article, which provides information about the recycling of Li-ion batteries, will contribute to the studies and research of the readers.

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Author Contribution

T. K., H. K., M. G., G. S., C. A., C.A., I.H., E. H., R.B., M.A., M.B.; Collected Data, Wrote the Paper. **T. K., M.B.;** Conceived and designed the analysis**. M.A., R.B.;** Performed the analysis. **H. K., M. G., G. S., C. A., C.A., I.H., E. H.;** Contributed Data.

References

[1]A. G. Olabi *et al.*, "Renewable Energy Systems: Comparisons, Challenges And Barriers, Sustainability İndicators, And The Contribution To UN Sustainable Development Goals," *Int. J. Thermofluids*, vol. 20, no. October, p. 100498, 2023, doi: 10.1016/j.ijft.2023.100498.
[2]T. Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari, and N. Prabaharan, "A Comprehensive Study Of Renewable Energy Sources: Classifications, Challenges And Suggestions.," *Energy Strateg. Rev.*, vol. 43, no. August, p. 100939, 2022, doi: 10.1016/j.esr.2022.100939.
[3]A. A. Kebede, T. Kalogiannis, J. Van Mierlo, and M. Berecibar, "A Comprehensive Review Of Stationary Energy Storage Devices For Large Scale Renewable Energy Sources Grid İntegration.," *Renew. Sustain. Energy Rev.*, vol. 159, p. 112213, 2022, doi: 10.1016/j.rser.2022.112213.
[4]W. F. . Meyers, B. Bell, and J. W. Simmon, "Electric Current-Producing Cell With Anydrous Organic Liquid Electrolyte.," *United States Pat. Off.*, vol. 28, no. 2, pp. 131–134, 1969.
[5]C. L. Batteries and M. Fowler, "Comparative Study of Equivalent Circuit Models Performance," *MDPI Batter.*, 2021.
[6]R. Van Noorden, "The Rechargeable Revolution A Better Battery.," *Nature*, vol. 507, pp. 26–28, 2014.
[7]R. S. Treptow, "A Practical Application Of Chemical Principles.," *J. Chem. Educ.*, vol. 80, no. 9, pp. 1015–1020, 2003, doi: 10.1021/ed080p1015.
[8]L. E. Asp, M. Johansson, G. Lindbergh, J. Xu, and D. Zenkert, "Structural Battery Composites:," *Funct. Compos. Struct.*, vol. 1, no. 4, 2019, doi: 10.1088/2631-6331/ab5571.
[9]Y. Zhao *et al.*, "A Review on Battery Market Trends, Second-Life Reuse, and Recycling," *Sustain. Chem.*, vol. 2, no. 1, pp. 167–205, 2021, doi: 10.3390/suschem2010011.

[10]L. Wang, B. Chen, J. Ma, G. Cui, and L. Chen, "Reviving Lithium Cobalt Oxide-Based Lithium Secondary Batteries-Toward A Higher Energy Density," *Chem. Soc. Rev.*, vol. 47, no. 17, pp. 6505–6602, 2018, doi: 10.1039/c8cs00322j.

[11]M. J. Lee, S. Lee, P. Oh, Y. Kim, and J. Cho, "High Performance Limn2o4 Cathode Materials Grown With Epitaxial Layered Nanostructure For Li-Ion Batteries.," *Nano Lett.*, vol. 14, no. 2, pp. 993–999, 2014, doi: 10.1021/nl404430e.

[12]F. Forte, M. Pietrantonio, S. Pucciarmati, M. Puzone, and D. Fontana, "Lithium İron Phosphate Batteries Recycling: An Assessment Of Current Status.," *Crit. Rev. Environ. Sci. Technol.*, vol. 51, no. 19, pp. 2232–2259, 2021, doi: 10.1080/10643389.2020.1776053.

[13]H. Karimi-Maleh, K. Cellat, K. Arıkan, A. Savk, F. Karimi, and F. Şen, "Palladium Nickel Nanoparticles Decorated On Functionalized MWCNT For High Precision Non-Enzymatic Glucose Sensing," *Mater. Chem. Phys.*, vol. 250, p. 123042, Aug. 2020, doi: 10.1016/j.matchemphys.2020.123042.

[14]A. Aygun, G. Sahin, R. N. E. Tiri, Y. Tekeli, and F. Sen, "Colorimetric Sensor Based on Biogenic Nanomaterials for High Sensitive Detection of Hydrogen Peroxide and Multi Metals," *Chemosphere*, vol. 339, p. 139702, Oct. 2023, doi: 10.1016/j.chemosphere.2023.139702.

[15]K. Arikan, H. Burhan, R. Bayat, and F. Sen, "Glucose Nano Biosensor With Nonenzymatic Excellent Sensitivity Prepared With Nickel Cobalt Nanocomposites On F-MWCNT," *Chemosphere*, vol. 291, p. 132720, Mar. 2022, doi: 10.1016/J.CHEMOSPHERE.2021.132720.

[16]A. Şavk et al., "Highly Monodisperse Pd-Ni Nanoparticles Supported On Rgo As A Rapid, Sensitive, Reusable And Selective Enzyme-Free Glucose Sensor," *Sci. Rep.*, vol. 9, no. 1, p. 19228, Dec. 2019, doi: 10.1038/s41598-019-55746-y.

[17]N. Korkmaz et al., "Biogenic silver nanoparticles synthesized via Mimusops elengi fruit extract, a study on antibiofilm, antibacterial, and anticancer activities," *J. Drug Deliv. Sci. Technol.*, vol. 59, p. 101864, Oct. 2020, doi: 10.1016/j.jddst.2020.101864.

[18]Z. Ozturk, F. Sen, S. Sen, and G. Gokagac, "The Preparation and Characterization of Nano Sized Pt–Pd/C Catalysts and Comparison of Their Superior Catalytic Activities for Methanol and Ethanol Oxidation," *J. Mater. Sci.*, vol. 47, no. 23, pp. 8134–8144, Dec. 2012, doi: 10.1007/s10853-012-6709-3.

[19]N. Lolak, E. Kuyuldar, H. Burhan, H. Goksu, S. Akocak, and F. Sen, "Composites of Palladium–Nickel Alloy Nanoparticles and Graphene Oxide for the Knoevenagel Condensation of Aldehydes with Malononitrile," *ACS Omega*, vol. 4, no. 4, pp. 6848–6853, Apr. 2019, doi: 10.1021/acsomega.9b00485.

[20]M. H. Calimli, M. S. Nas, H. Burhan, S. D. Mustafov, Ö. Demirbas, and F. Sen, "Preparation, Characterization and Adsorption Kinetics of Methylene Blue Dye in Reduced Graphene Oxide Supported Nanoadsorbents," *J. Mol. Liq.*, vol. 309, p. 113171, Jul. 2020, doi: 10.1016/j.molliq.2020.113171.

[21]B. Sen, E. Kuyuldar, B. Demirkan, T. Onal Okyay, A. Şavk, and F. Sen, "Highly Efficient Polymer Supported Monodisperse Ruthenium Nickel Nanocomposites for Dehydrocoupling of Dimethylamine Borane," *J. Colloid Interface Sci.*, vol. 526, pp. 480–486, Sep. 2018, doi: 10.1016/j.jcis.2018.05.021.

[22]S. Ertan, F. Şen, S. Şen, and G. Gökağaç, "Platinum Nanocatalysts Prepared With Different Surfactants for C1–C3 Alcohol Oxidations and Their Surface Morphologies by AFM," *J. Nanoparticle Res.*, vol. 14, no. 6, p. 922, Jun. 2012, doi: 10.1007/s11051-012-0922-5.

[23]B. Demirkan et al., "Palladium Supported on Polypyrrole/Reduced Graphene Oxide Nanoparticles for Simultaneous Biosensing Application of Ascorbic Acid, Dopamine, and Uric Acid," *Sci. Rep.*, vol. 10, no. 1, p. 2946, Feb. 2020, doi: 10.1038/s41598-020-59935-y.

[24]F. Şen, *Nanomaterials for Direct Alcohol Fuel Cells: Characterization, Design, and Electrocatalysis*. Elsevier, 2021. doi: 10.1016/B978-0-12-821713-9.09990-X.

[25]D. Deng, "Li-ion Batteries: Basics, Progress, and Challenges," *Energy Sci. Eng.*, vol. 3, no. 5, pp. 385–418, 2015, doi: 10.1002/ese3.95.

[26]J. Heelan et al., "Current and Prospective Li-Ion Battery Recycling and Recovery Processes," *Jom*, vol. 68, no. 10, pp. 2632–2638, 2016, doi: 10.1007/s11837-016-1994-y.

[27]D. Steward, A. Mayyas, and M. Mann, "Economics And Challenges Of Li-İon Battery Recycling From End-Of-Life Vehicles.," *Procedia Manuf.*, vol. 33, pp. 272–279, 2019, doi: 10.1016/j.promfg.2019.04.033.

[28]P. Kuchhal and U. C. Sharma, "Battery Waste Management," *Environ. Sci. Eng.*, vol. 5, no. March, pp. 141–155, 2019.

[29]J. F. Peters, M. Baumann, B. Zimmermann, J. Braun, and M. Weil, "The Environmental İmpact Of Li-Ion Batteries andThe Role Of Key Parameters," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 491–506, 2017, doi: 10.1016/j.rser.2016.08.039.

[30]S. Natarajan and V. Aravindan, "Burgeoning Prospects of Spent Lithium-Ion Batteries in Multifarious Applications," *Adv. Energy Mater.*, vol. 8, no. 33, pp. 1–16, 2018, doi: 10.1002/aenm.201802303.

[31]F. A. Unal, S. Ok, M. Unal, S. Topal, K. Cellat, and F. Şen, "Synthesis, Characterization, and Application of Transition Metals (Ni, Zr, and Fe) Doped TiO2 Photoelectrodes for Dye-Sensitized Solar Cells," *J. Mol. Liq.*, vol. 299, p. 112177, Feb. 2020, doi: 10.1016/j.molliq.2019.112177.

[32]K. Arikan, H. Burhan, E. Sahin, and F. Sen, "A sensitive, Fast, Selective, and Reusable Enzyme Free Glucose Sensor Based on Monodisperse AuNi Alloy Nanoparticles on Activated Carbon Support," *Chemosphere*, vol. 291, p. 132718, Mar. 2022, doi: 10.1016/j.chemosphere.2021.132718.

[33]R. Darabi et al., "Simultaneous determination of ascorbic acid, dopamine, and uric acid with a highly selective and sensitive reduced graphene oxide/polypyrrole-platinum nanocomposite modified electrochemical sensor," *Electrochim. Acta*, vol. 457, p. 142402, Jul. 2023, doi: 10.1016/J.ELECTACTA.2023.142402.

[34]H. Göksu, Y. Yıldız, B. Çelik, M. Yazıcı, B. Kılbaş, and F. Şen, "Highly Efficient and Monodisperse Graphene Oxide Furnished Ru/Pd Nanoparticles for the Dehalogenation of Aryl Halides via Ammonia Borane," *ChemistrySelect*, vol. 1, no. 5, pp. 953–958, Apr. 2016, doi: 10.1002/slct.201600207.

[35]B. Sen, S. Kuzu, E. Demir, S. Akocak, and F. Sen, "Polymer Graphene Hybride Decorated Pt Nanoparticles as Highly Efficient and Reusable Catalyst for the Dehydrogenation of Dimethylamine Borane at Room Temperature," *Int. J. Hydrogen Energy*, vol. 42, no. 36, pp. 23284–23291, Sep. 2017, doi: 10.1016/j.ijhydene.2017.05.112.

[36]M. Kurtay, H. G. Göksu, Haydar, H. Burhan, M. I. Ahamed, and F. Şen, "Magnetic Nanomaterials for Lithium-ion Batteries," in *Magnetic Nanomaterials for Lithium-ion Batteries*, 2020, pp. 123–147. doi: 10.21741/9781644900918-5.

[37]B. Sen, S. Kuzu, E. Demir, E. Yıldırır, and F. Sen, "Highly Efficient Catalytic Dehydrogenation of Dimethyl Ammonia Borane Via Monodisperse Palladium Nickel Alloy Nanoparticles Assembled on PEDOT," *Int. J. Hydrogen Energy*, vol. 42, no. 36, pp. 23307–23314, Sep. 2017, doi: 10.1016/j.ijhydene.2017.05.115.

[38]F. Şen and G. Gökağaç, "Activity of Carbon-Supported Platinum Nanoparticles toward Methanol Oxidation Reaction: Role of Metal Precursor and a New Surfactant, tert -Octanethiol," *J. Phys. Chem. C*, vol. 111, no. 3, pp. 1467–1473, Jan. 2007, doi: 10.1021/jp065809y.

[39]H. Kumar et al., "Fruit Extract Mediated Green Synthesis of Metallic Nanoparticles: A New Avenue in Pomology Applications," *Int. J. Mol. Sci.*, vol. 21, no. 22, p. 8458, Nov. 2020, doi: 10.3390/ijms21228458.

[40]E. Erken, Y. Yıldız, B. Kilbaş, and F. Şen, "Synthesis and Characterization of Nearly Monodisperse Pt Nanoparticles for C 1 to C 3 Alcohol Oxidation and Dehydrogenation of Dimethylamine-borane (DMAB)," *J. Nanosci. Nanotechnol.*, vol. 16, no. 6, pp. 5944–5950, Jun.

2016, doi: 10.1166/jnn.2016.11683.

[41]R. Darabi *et al.*, "Biogenic Platinum-Based Bimetallic Nanoparticles: Synthesis, Characterization, Antimicrobial Activity And Hydrogen Evolution," *Int. J. Hydrogen Energy*, vol. 48, no. 55, pp. 21270–21284, Jun. 2023, doi: 10.1016/j.ijhydene.2022.12.072.

[42]C. Demir, S. Keskin, and F. Şen, "ANOM Approach for Statistical Evaluation of Some Antioxidant Enzyme Activities," *Front. Chem.*, vol. 10, May 2022, doi: 10.3389/fchem.2022.894547.

[43]F. Göl, A. Aygün, A. Seyrankaya, T. Gür, C. Yenikaya, and F. Şen, "Green Synthesis And Characterization Of Camellia Sinensis Mediated Silver Nanoparticles For Antibacterial Ceramic Applications," *Mater. Chem. Phys.*, vol. 250, p. 123037, Aug. 2020, doi: 10.1016/J.MATCHEMPHYS.2020.123037.

[44]H. Burhan *et al.*, "Highly Efficient Carbon Hybrid Supported Catalysts Using Nano Architecture as Anode Catalysts for Direct Methanol Fuel Cells," *Int. J. Hydrogen Energy*, vol. 48, no. 17, pp. 6657–6665, Feb. 2023, doi: 10.1016/j.ijhydene.2021.12.141.

[45]Y. Wu *et al.*, "Hydrogen Generation From Methanolysis Of Sodium Borohydride Using Waste Coffee Oil Modified Zinc Oxide Nanoparticles And Their Photocatalytic Activities," *Int. J. Hydrogen Energy*, vol. 48, no. 17, pp. 6613–6623, Feb. 2023, doi: 10.1016/j.ijhydene.2022.04.177.

[46]A. Şavk, H. Aydın, K. Cellat, and F. Şen, "A Novel High Performance Non Enzymatic Electrochemical Glucose Biosensor Based on Activated Carbon Supported Pt-Ni Nanocomposite," *J. Mol. Liq.*, vol. 300, p. 112355, Feb. 2020, doi: 10.1016/j.molliq.2019.112355.

[47]B. Sen, B. Demirkan, A. Şavk, S. Karahan Gülbay, and F. Sen, "Trimetallic PdRuNi Nanocomposites Decorated on Graphene Oxide: A superior Catalyst for the Hydrogen Evolution Reaction," *Int. J. Hydrogen Energy*, vol. 43, no. 38, pp. 17984–17992, Sep. 2018, doi: 10.1016/j.ijhydene.2018.07.122.

[48]Y. Yildiz *et al.*, "Highly Monodisperse Pt/Rh Nanoparticles Confined in the Graphene Oxide for Highly Efficient and Reusable Sorbents for Methylene Blue Removal from Aqueous Solutions," *ChemistrySelect*, vol. 2, no. 2, pp. 697–701, Jan. 2017, doi: 10.1002/slct.201601608.

[49]J. T. Abrahamson *et al.*, "Excess Thermopower and the Theory of Thermopower Waves," *ACS Nano*, vol. 7, no. 8, pp. 6533–6544, Aug. 2013, doi: 10.1021/nn402411k.

[50]B. Şen, A. Aygün, T. O. Okyay, A. Şavk, R. Kartop, and F. Şen, "Monodisperse Palladium Nanoparticles Assembled on Graphene Oxide With the High Catalytic Activity and Reusability in the Dehydrogenation of Dimethylamine Borane," *Int. J. Hydrogen Energy*, vol. 43, no. 44, pp 20176–20182, Nov. 2018, doi: 10.1016/j.ijhydene.2018.03.175.

[51]R. Nagraik, A. Sharma, D. Kumar, S. Mukherjee, F. Sen, and A. P. Kumar, "Amalgamation Of Biosensors and Nanotechnology In Disease Diagnosis: Mini-Review," *Sensors Int.*, vol. 2, p. 100089, Jan. 2021, doi: 10.1016/J.SINTL.2021.100089.

[52]S. Günbatar, A. Aygun, Y. Karataş, M. Gülcan, and F. Şen, "Carbon Nanotube Based Rhodium Nanoparticles as Highly Active Catalyst for Hydrolytic Dehydrogenation of Dimethylamineborane at Room Temperature," *J. Colloid Interface Sci.*, vol. 530, pp. 321–327, Nov. 2018, doi: 10.1016/j.jcis.2018.06.100.

[53]F. Şen and G. Gökağaç, "Improving Catalytic Efficiency in the Methanol Oxidation Reaction by Inserting Ru in Face-Centered Cubic Pt Nanoparticles Prepared by a New Surfactant, tert -Octanethiol," *Energy & Fuels*, vol. 22, no. 3, pp. 1858–1864, May 2008, doi: 10.1021/ef700575t.

[54]V. Aravindan, Y. Lee, and S. Madhavi, "Research Progress on Negative Electrodes for Practical Li- Ion Batteries: Beyond Carbonaceous Anodes," *Adv. Energy Mater.*, vol. 5, no. 13, Jul. 2015, doi: 10.1002/aenm.201402225.

[55]N. Nitta, F. Wu, J. T. Lee, and G. Yushin, "Li-İon Battery Materials: Present And Future.," *Mater. Today*, vol. 18, no. 5, pp. 252–264, Jun. 2015, doi: 10.1016/j.mattod.2014.10.040.

[56]S. Yasa, O. Aydin, M. Al-Bujasim, B. Birol, and M. Gencten, "Recycling Valuable Materials From The Cathodes Of Spent Lithium-İon Batteries: A Comprehensive Review," *J. Energy Storage*, vol. 73, p. 109073, Dec. 2023, doi: 10.1016/j.est.2023.109073.

[57]C. A. F. Nason and Y. Xu, "Pre-İntercalation: A Valuable Approach For The İmprovement Of Post-Lithium Battery Materials," *eScience*, p. 100183, Sep. 2023, doi: 10.1016/j.esci.2023.100183.

[58]P. A. Nelson, S. Ahmed, K. G. Gallagher, and D. W. Dees, "Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Third Edition," Argonne, IL (United States), Mar. 2019. doi: 10.2172/1503280.

[59]P. P. R. M. L. Harks, F. M. Mulder, and P. H. L. Notten, "In Situ Methods For Li-İon Battery Research: A Review Of Recent Developments.," *J. Power Sources*, vol. 288, pp. 92–105, Aug. 2015, doi: 10.1016/j.jpowsour.2015.04.084.

[60]Y. Miao, L. Liu, Y. Zhang, Q. Tan, and J. Li, "An Overview Of Global Power Lithium-İon Batteries And Associated Critical Metal Recycling.," *J. Hazard. Mater.*, vol. 425, no. June 2021, p. 127900, 2022, doi: 10.1016/j.jhazmat.2021.127900.

[61]A. Kaya, "Sodyum-İyon Piller: Enerji Depolama Ve Dönüşüm İçin Ucuz Bir Çözümfile:///C:/Users/irem7/Desktop/1-s2.0-S0304389421028697-main.pdf," *Tez*, vol. 044, no. 2017, 2019.

[62]Y. Hu, Y. Yu, K. Huang, and L. Wang, "Development Tendency And Future Response About The Recycling Methods Of Spent Lithium-İon Batteries Based On Bibliometrics Analysis.," *J. Energy Storage*, vol. 27, no. August 2019, p. 101111, 2020, doi: 10.1016/j.est.2019.101111.

[63]L. Yun *et al.*, "Metallurgical And Mechanical Methods For Recycling Of Lithium-İon Battery Pack For Electric Vehicles.," *Resour. Conserv. Recycl.*, vol. 136, no. May, pp. 198–208, 2018, doi: 10.1016/j.resconrec.2018.04.025.

[64]P. H. Camargos, "Perspectives On Li-İon Battery Categories For Electric Vehicleapplications: A Review Of State Of The Art." pp. 19258–19268, 2022.

[65]M. Sanders, "Lithium-İon Battery Raw Material Supply And Demand 2016-2025," *Glob. Batter. Raw Mater. 2017, Held AABC 2017*, pp. 162–181, 2017.

[66]H. Ali, H. A. Khan, and M. G. Pecht, "Circular Economy Of Li Batteries: Technologies And Trends.," *J. Energy Storage*, vol. 40, no. March, p. 102690, 2021, doi: 10.1016/j.est.2021.102690.

[67]Y. Wang *et al.*, "Recent Progress On The Recycling Technology Of Li-İon Batteries.," *J. Energy Chem.*, vol. 55, pp. 391–419, Apr. 2021, doi: 10.1016/j.jechem.2020.05.008.

[68]L. li QU *et al.*, "Enhancement Of Leaching Of Cobalt And Lithium From Spent Lithium-İon Batteries By Mechanochemical Process.," *Trans. Nonferrous Met. Soc. China (English Ed.*, vol. 32, no. 4, pp. 1325–1335, 2022, doi: 10.1016/S1003-6326(22)65877-1.

[69]V. Chaudhary, P. Lakhera, V. Shrivastav, P. Kumar, and A. Deep, "Nanoporous Carbon/Cobalt Composite Derived from End-of-Life Lithium Cobalt Oxide-Type Lithium-Ion Batteries for Supercapacitor Applications," *Ind. Eng. Chem. Res.*, vol. 61, no. 50, pp. 18492–18502, 2022, doi: 10.1021/acs.iecr.2c03293.

[70]A. Verma, A. J. Henne, D. R. Corbin, and M. B. Shiflett, "Lithium and Cobalt Recovery from LiCoO2Using Oxalate Chemistry: Scale-Up and Techno-Economic Analysis," *Ind. Eng. Chem. Res.*, vol. 61, no. 15, pp. 5285–5294, 2022, doi: 10.1021/acs.iecr.1c04876.

[71]X. Liao *et al.*, "Feasibility Of Reduced İron Species For Promoting Li And Co Recovery From Spent Licoo2 Batteries Using A Mixed-Culture Bioleaching Process.," *Sci. Total Environ.*, vol. 830, p. 154577, 2022, doi: 10.1016/j.scitotenv.2022.154577.

[72]N. Peeters, K. Janssens, D. de Vos, K. Binnemans, and S. Riaño, "Choline Chloride-Ethylene Glycol Based Deep-Eutectic Solvents As

Lixiviants For Cobalt Recovery From Lithium-İon Battery Cathode Materials: Are These Solvents Really Green İn High-Temperature Processes?," *Green Chem.*, vol. 24, no. 17, pp. 6685–6695, 2022, doi: 10.1039/d2gc02075k.

[73]N. Peeters, K. Binnemans, and S. Riaño, "Solvometallurgical Recovery Of Cobalt From Lithium-İon Battery Cathode Materials Using Deep-Eutectic Solvents," *Green Chem.*, vol. 22, no. 13, pp. 4210–4221, 2020, doi: 10.1039/d0gc00940g.

[74]M. Liu, W. Ma, X. Zhang, Z. Liang, and Q. Zhao, "Recycling Lithium And Cobalt From Lıbs Using Microwave-Assisted Deep Eutectic Solvent Leaching Technology At Low-Temperature.," *Mater. Chem. Phys.*, vol. 289, no. June, p. 126466, 2022, doi: 10.1016/j.matchemphys.2022.126466.

[75]K. Turcheniuk, D. Bondarev, V. Singhal, and G. Yushin, "Ten Years Left To Redesign Lithium-İon Batteries.," *Nature*, vol. 559, no. 7715, pp. 467–470, Jul. 2018, doi: 10.1038/d41586-018-05752-3.

[76]E. Fan *et al.*, "Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects," *Chem. Rev.*, vol. 120, no. 14, pp. 7020–7063, Jul. 2020, doi: 10.1021/acs.chemrev.9b00535.

[77]L. Ingeborgrud and M. Ryghaug, "The Role Of Practical, Cognitive And Symbolic Factors İn The Successful İmplementation Of Battery Electric Vehicles İn Norway.," *Transp. Res. Part A Policy Pract.*, vol. 130, pp. 507–516, Dec. 2019, doi: 10.1016/j.tra.2019.09.045.

[78]X. Chen, D. Kang, J. Li, T. Zhou, and H. Ma, "Gradient And Facile Extraction Of Valuable Metals From Spent Lithium İon Batteries For New Cathode Materials Re-Fabrication.," *J. Hazard. Mater.*, vol. 389, p. 121887, May 2020, doi: 10.1016/j.jhazmat.2019.121887.

[79]T. Georgi-Maschler, B. Friedrich, R. Weyhe, H. Heegn, and M. Rutz, "Development Of A Recycling Process For Li-İon Batteries.," *J. Power Sources*, vol. 207, pp. 173–182, Jun. 2012, doi: 10.1016/j.jpowsour.2012.01.152.

[80]G. Harper *et al.*, "Recycling Lithium-İon Batteries From Electric Vehicles.," *Nature*, vol. 575, no. 7781, pp. 75–86, Nov. 2019, doi: 10.1038/s41586-019-1682-5.

[81]Y.-F. Meng *et al.*, "Concurrent Recycling Chemistry For Cathode/Anode İn Spent Graphite/Lifepo4 Batteries: Designing A Unique Cation/Anion-Co-Workable Dual-İon Battery.," *J. Energy Chem.*, vol. 64, pp. 166–171, Jan. 2022, doi: 10.1016/j.jechem.2021.04.047.

[82]M.-C. Fan *et al.*, "Room-Temperature Extraction Of İndividual Elements From Charged Spent Lifepo4 Batteries.," *Rare Met.*, vol. 41, no. 5, pp. 1595–1604, May 2022, doi: 10.1007/s12598-021-01919-6.

[83]W. Liu, K. Li, W. Wang, Y. Hu, Z. Ren, and Z. Zhou, "Selective Leaching Of Lithium İons From <Scp> Lifepo 4 </Scp> Powders Using Hydrochloric Acid And Sodium Hypochlorite System.," *Can. J. Chem. Eng.*, vol. 101, no. 4, pp. 1831–1841, Apr. 2023, doi: 10.1002/cjce.24617.

[84]B. Gangaja, S. Nair, and D. Santhanagopalan, "Reuse, Recycle, and Regeneration of LiFePO 4 Cathode from Spent Lithium-Ion Batteries for Rechargeable Lithium- and Sodium-Ion Batteries," *ACS Sustain. Chem. Eng.*, vol. 9, no. 13, pp. 4711–4721, Apr. 2021, doi: 10.1021/acssuschemeng.0c08487.

[85]W. Zou *et al.*, "High-Efficiency Core-Shell Magnetic Heavy-Metal Absorbents Derived From Spent-Lifepo4 Battery," *J. Hazard. Mater.*, vol. 402, p. 123583, Jan. 2021, doi: 10.1016/j.jhazmat.2020.123583.

[86]X.-H. Yue, C.-C. Zhang, W.-B. Zhang, Y. Wang, and F.-S. Zhang, "Recycling Phosphorus From Spent Lifepo4 Battery For Multifunctional Slow-Release Fertilizer Preparation And Simultaneous Recovery Of Lithium.," *Chem. Eng. J.*, vol. 426, p. 131311, Dec. 2021, doi: 10.1016/j.cej.2021.131311.

[87]C. Ma, M. Svärd, and K. Forsberg, "Recycling Cathode Material Lico1/3Ni1/3Mn1/3O2 By Leaching With A Deep Eutectic Solvent And Metal Recovery With Antisolvent Crystallization.," *Resour. Conserv. Recycl.*, vol. 186, no. August, 2022, doi: 10.1016/j.resconrec.2022.106579.

[88]X.-H. Yue and F.-S. Zhang, "Recycling Spent Lifepo4 Battery For Fabricating Visible-Light Photocatalyst With Adsorption-Photocatalytic Synergistic Performance And Simultaneous Recovery Of Lithium And Phosphorus.," *Chem. Eng. J.*, vol. 450, p. 138388, Dec. 2022, doi: 10.1016/j.cej.2022.138388.

[89]H. Chu, C. Qian, B. Tian, S. Qi, J. Wang, and B. Xin, "Pyrometallurgy Coupling Bioleaching For Recycling Of Waste Printed Circuit Boards.," *Resour. Conserv. Recycl.*, vol. 178, p. 106018, Mar. 2022, doi: 10.1016/j.resconrec.2021.106018.

[90]B. Zhang *et al.*, "A Sodium Salt-Assisted Roasting Approach Followed By Leaching For Recovering Spent Lifepo4 Batteries.," *J. Hazard. Mater.*, vol. 424, p. 127586, Feb. 2022, doi: 10.1016/j.jhazmat.2021.127586.

[91]J. Kumar, X. Shen, B. Li, H. Liu, and J. Zhao, "Selective Recovery Of Li And Fepo4 From Spent Lifepo4 Cathode Scraps By Organic Acids And The Properties Of The Regenerated Lifepo4.," *Waste Manag.*, vol. 113, pp. 32–40, Jul. 2020, doi: 10.1016/j.wasman.2020.05.046.

[92]Y. Zhao *et al.*, "Regeneration And Reutilization Of Cathode Materials From Spent Lithium-İon Batteries.," *Chem. Eng. J.*, vol. 383, p. 123089, Mar. 2020, doi: 10.1016/j.cej.2019.123089.

[93]M. Fan *et al.*, "In Situ Electrochemical Regeneration of Degraded LiFePO 4 Electrode with Functionalized Prelithiation Separator," *Adv. Energy Mater.*, vol. 12, no. 18, May 2022, doi: 10.1002/aenm.202103630.

[94]W. Zhang, D. Wang, and W. Zheng, "A Semiconductor-Electrochemistry Model For Design Of High-Rate Li İon Battery.," *J. Energy Chem.*, vol. 41, pp. 100–106, Feb. 2020, doi: 10.1016/j.jechem.2019.04.018.

[95]S. S. Zhang, "Identifying Rate Limitation And A Guide To Design Of Fast- Charging Li- İon Battery.," *InfoMat*, vol. 2, no. 5, pp. 942–949, Sep. 2020, doi: 10.1002/inf2.12058.

[96]J. Wang *et al.*, "Electrochemical technologies for lithium recovery from liquid resources: A Rewiew," *Renew. Sustain. Energy Rev.*, vol. 154, p. 111813, Feb. 2022, doi: 10.1016/j.rser.2021.111813.

[97]P. Xu *et al.*, "Materials For Lithium Recovery From Salt Lake Brine.," *J. Mater. Sci.*, vol. 56, no. 1, pp. 16–63, Jan. 2021, doi: 10.1007/s10853-020-05019-1.

[98]Z. Wang, Y. Huang, X. Wang, D. Wu, and X. Wu, "Advanced Solid-State Electrolysis for Green and Efficient Spent LiFePO 4 Cathode Material Recycling: Prototype Reactor Tests," *Ind. Eng. Chem. Res.*, vol. 61, no. 34, pp. 12318–12328, Aug. 2022, doi: 10.1021/acs.iecr.2c02266.

[99]H. Gao *et al.*, "Efficient Direct Recycling of Degraded LiMn 2 O 4 Cathodes by One-Step Hydrothermal Relithiation," *ACS Appl. Mater. Interfaces*, vol. 12, no. 46, pp. 51546–51554, Nov. 2020, doi: 10.1021/acsami.0c15704.

[100]M. Sarkar, R. Hossain, and V. Sahajwalla, "Sustainable Recovery And Resynthesis Of Electroactive Materials From Spent Li-İon Batteries To Ensure Material Sustainability.," *Resour. Conserv. Recycl.*, vol. 200, p. 107292, Jan. 2024, doi: 10.1016/j.resconrec.2023.107292.

[101]D. Liu, Z. Su, and L. Wang, "Pyrometallurgically Regenerated Limn2o4 Cathode Scrap Material And İts Electrochemical Properties.," *Ceram. Int.*, vol. 47, no. 1, pp. 42–47, Jan. 2021, doi: 10.1016/j.ceramint.2020.06.037.

[102]T. Zhao *et al.*, "Direct Selective Leaching Of Lithium From İndustrial-Grade Black Mass Of Waste Lithium-İon Batteries Containing Lifepo4 Cathodes.," *Waste Manag.*, vol. 171, pp. 134–142, Nov. 2023, doi: 10.1016/j.wasman.2023.08.030.

[103]M. He *et al.*, "Sustainable And Facile Process For Li2co3 And Mn2o3 Recovery From Spent Limn2o4 Batteries Via Selective Sulfation

With Waste Copperas.," *J. Environ. Chem. Eng.*, vol. 11, no. 3, p. 110222, Jun. 2023, doi: 10.1016/j.jece.2023.110222.

[104]Y. Chen, N. Liu, F. Hu, L. Ye, Y. Xi, and S. Yang, "Thermal Treatment And Ammoniacal Leaching For The Recovery Of Valuable Metals From Spent Lithium-İon Batteries.," *Waste Manag.*, vol. 75, pp. 469–476, May 2018, doi: 10.1016/j.wasman.2018.02.024.

[105]C. Wu *et al.*, "Cost-Effective Recycling Of Spent Limn2o4 Cathode Via A Chemical Lithiation Strategy.," *Energy Storage Mater.*, vol. 55, pp. 154–165, Jan. 2023, doi: 10.1016/j.ensm.2022.11.043.

[106]J. Wang *et al.*, "A Green Process For Recycling And Synthesis Of Cathode Materials Limn 2 O 4 From Spent Lithium-İon Batteries Using Citric Acid.," *RSC Adv.*, vol. 12, no. 36, pp. 23683–23691, 2022, doi: 10.1039/D2RA04391B.

[107]J. Zhou, J. Bing, J. Ni, X. Wang, and X. Guan, "Recycling The Waste Limn2o4 Of Spent Li-İon Batteries By Ph Gradient İn Neutral Water Electrolyser," *Mater. Today Sustain.*, vol. 20, p. 100205, Dec. 2022, doi: 10.1016/j.mtsust.2022.100205.

[108]A. Mohanty, L. B. Sukla, S. Nayak, and N. Devi, "Selective Recovery And İntensification Of Mn From Spent Limn 2 O 4 Using Sulfuric Acid As Lixiviant And Na-D2ehpa As Extractant.," *Geosystem Eng.*, vol. 25, no. 5–6, pp. 246–255, Nov. 2022, doi: 10.1080/12269328.2022.2127426.

[109]L. Yao, Y. Xi, H. Han, W. Li, C. Wang, and Y. Feng, "Limn2o4 Prepared From Waste Lithium İon Batteries Through Sol-Gel Process," *J. Alloys Compd.*, vol. 868, p. 159222, Jul. 2021, doi: 10.1016/j.jallcom.2021.159222.

[110]O. Dolotko, N. Gehrke, M. Knapp, and H. Ehrenberg, "Mechanochemically İnduced Hydrometallurgical Method For Recycling D-Elements From Li-İon Battery Cathodes.," *J. Alloys Compd.*, p. 172884, Nov. 2023, doi: 10.1016/j.jallcom.2023.172884.

[111]R. Tao, P. Xing, H. Li, Z. Cun, Z. Sun, and Y. Wu, "In Situ Reduction Of Cathode Material By Organics And Anode Graphite Without Additive To Recycle Spent Electric Vehicle Limn2o4 Batteries.," *J. Power Sources*, vol. 520, p. 230827, Feb. 2022, doi: 10.1016/j.jpowsour.2021.230827.

[112]Z. Liu, H. Chen, D. Wang, X. Zhou, and P. Hu, "Metal Recovery from Spent LiMn2O4 Cathode Material Based on Sulfating Roasting with NaHSO4·H2O and Water Leaching," *J. Sustain. Metal.*, vol. 8, no. 2, pp. 684–699, Jun. 2022, doi: 10.1007/s40831-022-00519-7.

[113]J. Han, L. Chen, X. Zhong, X. Wei, and W. Qin, "A Promising Method For Recovery Of Limn2o4 And Graphite From Waste Lithium-İon Batteries: Roasting Enhanced Flotation.," *J. Cent. South Univ.*, vol. 29, no. 9, pp. 2873–2887, Sep. 2022, doi: 10.1007/s11771-022-5127-1.

[114]S. He and Z. Liu, "Efficient Process For Recovery Of Waste Limn2o4 Cathode Material: Low-Temperature (NH4)2SO4 Calcination Mechanisms And Water-Leaching Characteristics.," *Waste Manag.*, vol. 108, pp. 28–40, May 2020, doi: 10.1016/j.wasman.2020.04.030.

[115]S. Pindar and N. Dhawan, "Recycling Of Discarded Coin Cells For Recovery Of Metal Values.," *Miner. Eng.*, vol. 159, p. 106650, Dec. 2020, doi: 10.1016/j.mineng.2020.106650.

[116]J. Shi *et al.*, "Sulfation Roasting Mechanism for Spent Lithium-Ion Battery Metal Oxides Under SO2-O2-Ar Atmosphere," *JOM*, vol. 71, no. 12, pp. 4473–4482, Dec. 2019, doi: 10.1007/s11837-019-03800-5.

[117]M. He *et al.*, "Combined Pyro-Hydrometallurgical Technology For Recovering Valuable Metal Elements From Spent Lithium-İon Batteries: A Review Of Recent Developments.," *Green Chem.*, vol. 25, no. 17, pp. 6561–6580, 2023, doi: 10.1039/D3GC01077E.

[118]J. Liang, D. Wang, L. Wang, H. Li, W. Cao, and H. Yan, "Electrochemical process for recovery of metallic Mn from waste LiMn2O4-based Li-ion batteries in NaCl−CaCl2 melts," *Int. J. Miner. Metal. Mater.*, vol. 29, no. 3, pp. 473–478, Mar. 2022, doi: 10.1007/s12613-020-2144-7.

[119]Ö. F. Özcan, T. Karadağ, M. Altuğ, and Ö. F. Özgüven, "A Review Study On The Characteristics And Advantages Of Battery Chemicals Used İn Electric Vehicles.," *Gazi Univ. J. Sci.*, vol. 8, no. 2, pp. 276–298, 2021.

[120]S. Tez, "Fen Bilimleri Enstitüsü Lityum İyon Piller İçin NMC / Karbon Hibrit Kompozitlerin Sentezi ve Elektrokimyasal Karakterizasyonu," pp. 10–30, 2018.

[121]W. Y. Wang, C. H. Yen, J. L. Lin, and R. Bin Xu, "Recovery Of High-Purity Metallic Cobalt From Lithium Nickel Manganese Cobalt Oxide (NMC)-Type Li-İon Battery.," *J. Mater. Cycles Waste Manag.*, vol. 21, no. 2, pp. 300–307, 2019, doi: 10.1007/s10163-018-0790-x.

[122]G. Destekl and V. E. Elektrok, "Doktora tezi," 2022.

[123]R. H. Balcı and M. Sertsöz, "Farklı tip anot ve katot bazlı Li-iyon pillerinin küresel ısınma etkisinin (GWI) hesaplanması Calculating the global warming impact (GWI) of different types of anode and cathode based Li-ion batteries".

[124]O. Celep, E. Y. Yazici, H. Deveci, and C. Dorfling, "Recovery Of Lithium, Cobalt And Other Metals From Lithium-İon Batteries.," *Pamukkale Univ. J. Eng. Sci.*, vol. 29, no. 4, pp. 384–400, 2023, doi: 10.5505/pajes.2022.98793.

[125]P. Halil and İ. Zeybek, "International Online Conferences on Full Texts Book," pp. 30–40, 2021.

[126]S. Ilyas, R. Ranjan Srivastava, V. K. Singh, R. Chi, and H. Kim, "Recovery Of Critical Metals From Spent Li-İon Batteries: Sequential Leaching, Precipitation, And Cobalt–Nickel Separation Using Cyphos Il104.," *Waste Manag.*, vol. 154, no. October, pp. 175–186, 2022, doi: 10.1016/j.wasman.2022.10.005.

[127]H. Wang *et al.*, "Green and Low-Cost Approach for Recovering Valuable Metals from Spent Lithium-Ion Batteries," *Ind. Eng. Chem. Res.*, vol. 62, no. 9, pp. 3973–3984, 2023, doi: 10.1021/acs.iecr.2c02802.

[128]W. Xuan, A. Chagnes, X. Xiao, R. T. Olsson, and K. Forsberg, "Antisolvent Precipitation for Metal Recovery from Citric Acid Solution in Recycling of NMC Cathode Materials," *Metals (Basel).*, vol. 12, no. 4, pp. 1–14, 2022, doi: 10.3390/met12040607.

[129]P. M. Guarango, "Çinkur Atıklarından Metal Kazanımında Kolin Klorür - Üre Derin Ötektik Çözücüsünün Kullanımı," no. 8.5.2017, pp. 2003–2005, 2022.

[130]M. A. Topçu and A. Rüşen, "Investigation of Use of Deep Eutectic Solvent on Copper Recovery from Copper Anode Slag," *J. Eng. Archit. Fac. Eskişehir Osmangazi Univ.*, vol. 28, no. 3, pp. 308–320, 2020.

[131]Y. Luo, L. Ou, and C. Yin, "High-Efficiency Recycling Of Spent Lithium-İon Batteries: A Double Closed-Loop Process.," *Sci. Total Environ.*, vol. 875, no. February, p. 162567, 2023, doi: 10.1016/j.scitotenv.2023.162567.

[132]T. Yang *et al.*, "An Effective Relithiation Process for Recycling Lithium-Ion Battery Cathode Materials," *Adv. Sustain. Syst.*, vol. 4, no. 1, pp. 4–9, 2020, doi: 10.1002/adsu.201900088.

[133]S. Windisch-Kern, A. Holzer, C. Ponak, T. Hochsteiner, and H. Raupenstrauch, "Thermal Analysis Of Lithium İon Battery Cathode Materials For The Development Of A Novel Pyrometallurgical Recycling Approach.," *Carbon Resour. Convers.*, vol. 4, no. December 2020, pp. 184–189, 2021, doi: 10.1016/j.crcon.2021.04.005.

[134]G. Zhang, X. Yuan, C. Y. Tay, Y. He, H. Wang, and C. Duan, "Selective Recycling Of Lithium From Spent Lithium-İon Batteries By Carbothermal Reduction Combined With Multistage Leaching.," *Sep. Purif. Technol.*, vol. 314, no. 1, p. 123555, 2023, doi: 10.1016/j.seppur.2023.123555.

[135]Z. Yan, A. Sattar, and Z. Li, "Priority Lithium Recovery From Spent Li-İon Batteries Via Carbothermal Reduction With Water Leaching.," *Resour. Conserv. Recycl.*, vol. 192, no. February, p. 106937, 2023, doi: 10.1016/j.resconrec.2023.106937.

[136]G. S. Bhandari and N. Dhawan, "Gaseous Reduction Of NMC-Type Cathode Materials Using Hydrogen For Metal Recovery.," *Process Saf. Environ. Prot.*, vol. 172, no. August 2022, pp. 523–534, 2023, doi: 10.1016/j.psep.2023.02.053.

[137]Z. Liang *et al.*, "Mechanochemically Assisted Persulfate Activation For The Facile Recovery Of Metals From Spent Lithium İon Batteries," *Waste Manag.*, vol. 150, no. July, pp. 290–300, 2022, doi: 10.1016/j.wasman.2022.07.014.

[138]İ. E. Çuhadar, F. Mennik, N. İ. Dinç, A. Gül, and F. Burat, "Characterization And Recycling Of Lithium Nickel Manganese Cobalt Oxide Type Spent Mobile Phone Batteries Based On Mineral Processing Technology,"," *J. Mater. Cycles Waste Manag.*, vol. 25, no. 3, pp. 1746–1759, 2023, doi: 10.1007/s10163-023-01652-5.

[139]H. Qiu, C. Peschel, M. Winter, S. Nowak, J. Köthe, and D. Goldmann, "Recovery of Graphite and Cathode Active Materials from Spent Lithium-Ion Batteries by Applying Two Pretreatment Methods and Flotation Combined with a Rapid Analysis Technique," *Metals (Basel).*, vol. 12, no. 4, 2022, doi: 10.3390/met12040677.

[140]J. Liu *et al.*, "Efficient Liberation Of Electrode Materials İn Spent Lithium-İon Batteries Using A Cryogenic Ball Mill," *J. Environ. Chem. Eng.*, vol. 9, no. 5, p. 106017, 2021, doi: 10.1016/j.jece.2021.106017.

[141]J. Neumann *et al.*, "Recycling of Lithium- Ion Batteries—Current State of the Art, Circular Economy, and Next Generation Recycling," *Adv. Energy Mater.*, vol. 12, no. 17, May 2022, doi: 10.1002/aenm.202102917.

[142]T. Ercan, N. C. Onat, N. Keya, O. Tatari, N. Eluru, and M. Kucukvar, "Autonomous Electric Vehicles Can Reduce Carbon Emissions And Air Pollution İn Cities," *Transp. Res. Part D Transp. Environ.*, vol. 112, p. 103472, Nov. 2022, doi: 10.1016/j.trd.2022.103472.

[143]Y. Qiao *et al.*, "Recycling Of Graphite Anode From Spent Lithium- İon Batteries: Advances And Perspectives," *EcoMat*, vol. 5, no. 4, Apr. 2023, doi: 10.1002/eom2.12321.

[144]R. P. Sheth, N. S. Ranawat, A. Chakraborty, R. P. Mishra, and M. Khandelwal, "The Lithium-Ion Battery Recycling Process from a Circular Economy Perspective—A Review and Future Directions," *Energies*, vol. 16, no. 7, p. 3228, Apr. 2023, doi: 10.3390/en16073228.

[145]M. Bhar, S. Ghosh, S. Krishnamurthy, K. Yalamanchili, and S. K. Martha, "Electrochemical Compatibility of Graphite Anode from Spent Li-Ion Batteries: Recycled via a Greener and Sustainable Approach," *ACS Sustain. Chem. Eng.*, vol. 10, no. 23, pp. 7515–7525, Jun. 2022, doi: 10.1021/acssuschemeng.2c00554.