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Alloy Design and Optimization of Heat Treatment Cycle to Develop Ultra High Strength with Superior Ductility Bainitic Steel

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Abstract

Bainitic steel with YS> 600 MPa, UTS>1100 MPa and TE>20 % was developed in the present study with alloy design and optimization of heat treatment cycle. The steel with a chemical composition (wt.%) 0.2C-1.7%Si-2%Mn-0.9%Cr-0.2%C-0.18%Mo-0.07Nb-0.04Ti was induction melted and forged followed by slicing to 2mm thick sheets. The sheets were then subjected to inter critical annealing with 70% austenite and fully austenitized (above A_3) followed by salt bath holding in the range of 350 to 480ºC. YS, UTS and TE decreased in the case of inter critical annealing followed by increase in salt bath holding temperature due to the coarser lath structure of the bainites whereas the UTS increased with drastic decrease in the elongation and no significant change in the YS for the steel austenitized above A_3 followed by increase in bainitic holding temperature due to the transformation of globular type bainite to lath type bainites and their further coarsening. It was found that the steel austenitized above A_3 followed by salt bath holding at 350ºC gives the best properties due to the presence of granular type bainite in the range of 50-55% along with fine precipitates in addition to the TRIP effect for the presence of 10% retained austenite. Presence of fine precipitates of micro alloying elements further improves the mechanical properties of the steel.

Keywords: bainitic steel, heat treatment, granular bainite, lathe bainite, ultra high strength and superior ductility

1. Introduction

Bainitic steel are known to exhibit high strength and hardness and also a high level of toughness (F G Caballero, et al., 2006). The detrimental effect of cementite can be suppressed by addition of silicon above 1.5% which has very low solubility in cementite and greatly retard its growth from austenite (F G Caballero, et al., 2006; F G Caballero, et al., 2001; E. Jezierska, J. Dworecka & K. Rozniatowski, 2014). Hence, the rejected carbon from the bainitic ferrite enriches the residual austenite to stabilize it to room temperature. The existence of retained austenite promotes the TRIP effect during deformation to give ultra high strength and ductility aided by fine gran structure in the steel (Chengjia Shang, Xinlai He & Huaxin Hou, 2010). Suppressing the cementite formation to develop carbide free bainites and nano bainites with the nano size precipitation and fine bainitic laths with the addition of suitable alloying elements in the steel are growing demand for their excellent mechanical properties (V. C. Igwemezie & P. C. Agu, 2014; Avanish Kumar & Aparna Singh, 2021). There are several terminology in bainitic steels such as carbide free bainite, trip aided bainitic ferrite (Gopal Sanyal, 2023; Jianhao Yan, et al., 2024; K. Hausmann, D. Krizan, A. Pichler & E. Werner, 2013), lower bainite (H.K.D.H. Bhadeshia, 1980; G. Spanos, H.S. Fang & H.I. Aaronson, 1990), upper bainite (G. Spanos, H.S. Fang & H.I. Aaronson, 1990; T. Furuhara, H. Kawata, S. Morito & T. Maki, 2006; P. Retzl & E. Kozeschnik, 2024), granular bainite (Z.X. Qiao, et al., 2009; David De-Castro, et al., 2022; R. M. Jentner, et al., 2023), lathe bainite and plate (C P Luo & Jiangwen Liu, 2006; Adam Skowronek, et al., 2022), nano bainite etc (Avanish Kumar & Aparna Singh, 2021) which makes confusion to the researchers although some of them implies the same group of the bainitic steels.

Lower bainite consists of fine needle like plates or laths with the carbides precipitated within the laths. The microstructure of upper bainite consists of fine plates of ferrite grow in clusters called sheaves. Within each sheaf the plates are parallel and of identical crystallographic orientation, each with a well-defined crystallographic habit. The individual plates in a sheaf are often called the 'sub-units' of bainite. They are usually separated by low-misorientation boundaries or by cementite particles (H.K.D.H. Bhadeshia, 1980; G. Spanos, H.S. Fang & H.I. Aaronson, 1990; T. Furuhara, et al., 2006; P. Retzl, E. Kozeschnik, 2024).

Granular bainite is a term frequently used to describe the bainite that occurs during continuous cooling transformation, widely used in industry, where most steels undergo non-isothermal heat treatments. Microstructure of granular bainite forms gradually during cooling to form coarse structure of the sheaves of bainite which under optical microstructure appears as blocks of bainite and austenite. A characteristic of granular bainite is the lack of carbides in the microstructure where carbon that is partitioned from the bainitic ferrite stabilises the residual austenite, so that the final microstructure contains both retained austenite and some high carbon martensite in addition to the bainitic ferrite (Z.X. Qiao, et al., 2009; David De-Castro, et al., 2022; R. M. Jentner, S. P. Tsai, et al., 2023).

The carbide free bainite or TRIP aided bainitic ferrite where precipitation of cementite during bainitic transformation can be suppressed by alloying the steel with silicon. The carbon that is rejected from the bainitic ferrite enriches the residual austenite, thereby stabilising it down to ambient temperature. The microstructure obtained consists of bainitic ferrite laths interwoven with thin films of untransformed retained austenite (Gopal Sanyal, 2023; Jianhao Yan, et al., 2024; K. Hausmann, et al., 2013; F.G. Caballero, 2012).

Nano bainite microstructure is an elegant mixture of interwoven plates of bainitic ferrite and thin films of C-enriched retained austenite, both with tens of nm in thickness (Avanish Kumar & Aparna Singh, 2021; X.F. Yu, et al., 2022).

2. Experimental Plan

A steel was designed and subjected to induction melting and forging to get billet of 70*70 mm^2 cross section for the development of ultra high strength bainitic steel. The billet was then sliced to 2 mm thick sheets in an EDM machine to further heat treatment in a muffle furnace with the arrangement of salt bath. The chemical composition of the steel was obtained through SPECTRO make OES. The critical temperatures of the steel was obtained by constructing the CCT, TTT diagram through JMatPro Software. The phase field and volume fraction of phase were obtained through Thermos-Calc software. The steel samples were subjected to inter critical annealing at 800ºC (with the aim of two phase of 70% austenite and 30% ferrite) and above Ac_3 temperature at 880ºC (with the aim of 100% austenite) for 5 min followed by salt bath quenching and holding for 5 min in the temperatures such as 350, 400, 450 and 480ºC and then water quenched. Subsize tensile specimens were made from the heat treated samples according to ASTME8 and tensile tested in a Zwick/Roell make 250 kN tensile testing machine at standard strain rate of 0.008/s. Microstructure observations were conducted through an optodigital Olympus make optical microstructure and Hitachi make scanning electron microscope after sample preparation with the standard metallography technique.

3. Results and Discussion

3.1 Chemical Composition

Chemical composition of the steel is shown in Table 1. The steel is having 0.2%C and 2% Mn which helps in austenite stabilization and hardenability and the 1.6% Si which suppresses the cementite formation additionally helps in austenite stabilization in the steel (Lucia Morales-Rivas, 2022). Around 0.9% Cr facilitates metal carbide formation and significantly improve the hardness and hardenability, while Cu improves the ductility, and Mo gives solid solution strength and reduces the susceptibility of temper embrittlement in the steel. In addition to hardenability C, Mn and Cr helps in controlling the transformation temperatures (Radhakanta Rana, et al., 2024). C, Si and Mo acts as the most powerful austenite solid solution strengtheners. Micro alloying such as Nb and Ti helps in grain refinement in the hot deformation stage to give fine gran structure (E. Jezierska, J. Dworecka & K. Rozniatowski, 2014). Hence, with the alloying and micro alloying of the steel resulted in increase in the strength and ductility of the steel.

The TTT diagram of the steel with the critical temperatures and heat treatment cycle is shown in Figure 1. The phase diagram of the steel and volume fraction of phase obtained through Thermos-Calc software is shown in Figure 2. The steel subjected to austenitization at 800 and 880ºC where 800ºC corresponds to 70% austenite and 880ºC corresponds to 100% austenite.

Table 1. Chemical composition of the steel (wt. %)

C	Mn	S	P	Si	Al	Cr	Ni	Cu	Nb	V	Ti	Mo	B

0.213	2.07	0.037	0.056	1.71	0.025	0.899	0.045	0.213	0.069	0.005	0.038	0.176	0.0017

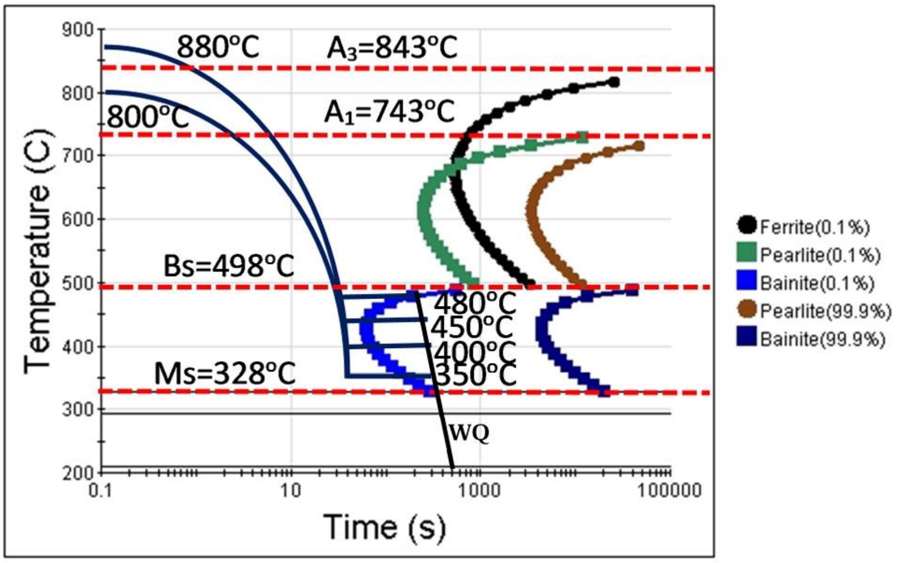

Figure 1. TTT diagram obtained through JMat Pro Software with the critical temperatures; B_s, M_s, A_1 and A_3 along with the heat treatment cycle

The steel was held in the salt bath in the temperature from 350 to 480ºC to vary the bainite content in the steel from lower bainite to upper bainite with the variation in their volume fraction and morphology which changes the mechanical properties of the steel.

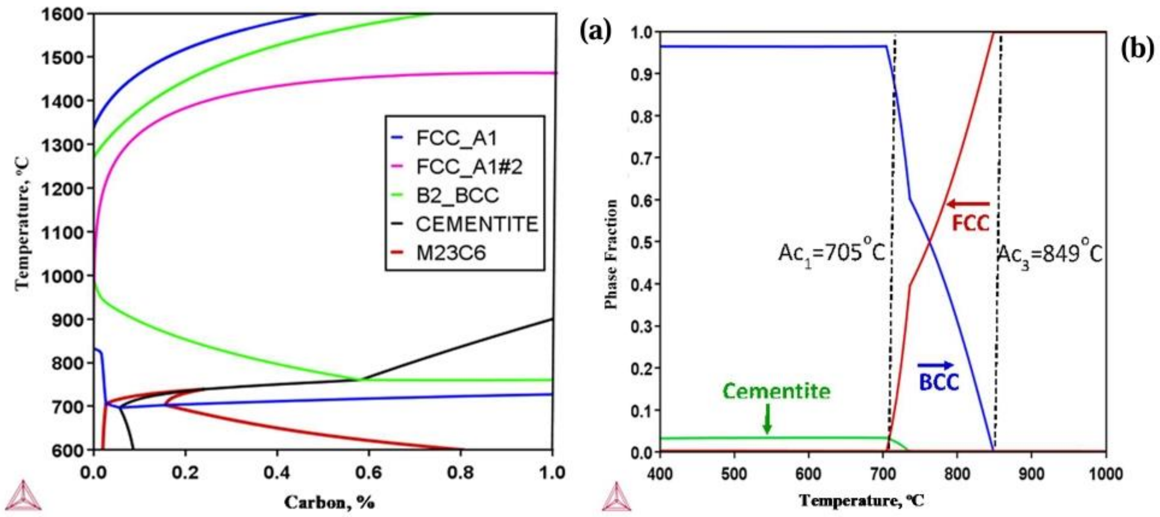

Figure 2. (a) Phase diagram and (b) Phase volume fraction of the steel obtained through Thermos-Calc software

3.2 Mechanical Properties

Figure 3 shows the engineering stress strain diagram of the steel inter critical annealed followed by salt bath holding in the temperature range of 350 to 480ºC. The mechanical properties of the steel at different bainitic holding temperature have been summarized in Table 2. The mechanical properties such as YS, UTS and TE were plotted against the bainitic holding temperature shown in Figure 4. There is very high ultimate tensile strength (>1100MPaUTS) and very low total elongation (<5%) found in the as-hot deformed steel. Bainitic holding at 350ºC resulted in about 50MPa decrease in strength while increase in yield strength around 30MPa and total elongation to >16%. With further increase in bainitic holding temperature no significant change in the properties found. A very small decrease in yield strengths and elongation found with the increase in the bainitic holding temperature. The hardness of the steels was increased with increase in the bainitic holding temperature.

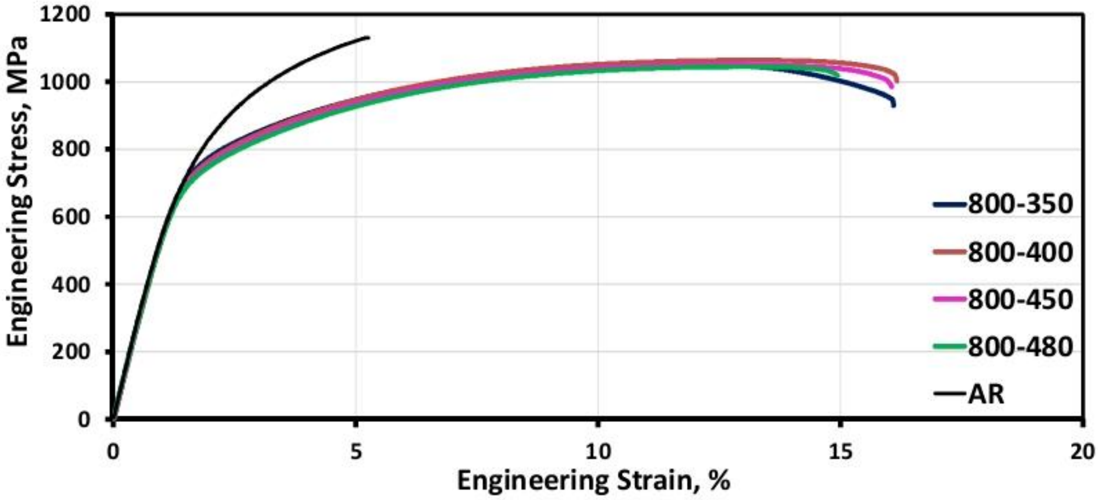

Figure 3. Engineering stress-strain diagram of the inter-critical austenitization followed by bainitic holding steel

Table 2. Mechanical properties in inter critical annealing followed by bainitic holding

Austempering Temp. °C		Austenitization Temperature- 800°C				
	YS, MPa	UTS, MPa	TE, %	YR	UTS*TE, GPa.%	Hv0.5
AR	642	1101	4.75	0.58	5.25	438
350	676	1053	15.55	0.64	16.38	402
400	661	1061	14.17	0.62	15.04	407
450	648	1055	15.83	0.61	16.70	418
480	633	1033	12.76	0.61	13.21	502

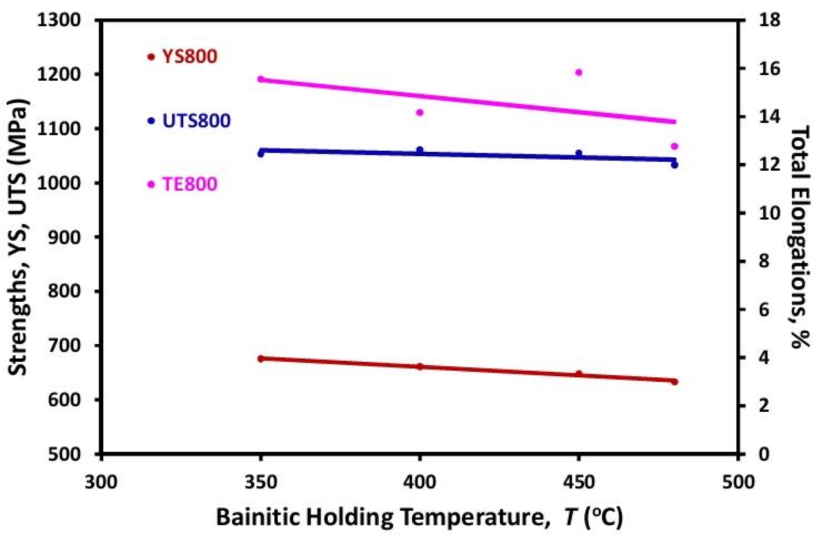

Figure 4. Change in YS, UTS and TE of the inter-critical austenitization of the steel followed by bainitic holding

The steel showed ultra high strength >1000MPa, yield strength >630MPa and total elongation >12.5% in all the bainitic holding temperature with the best properties at the lowest bainitic holding temperature of 350ºC with YS>670MPa, UTS>1050MPa and TE>15.5% with the yield ratio >0.60 with the UTS*TE>16GPa. %.

Figure 5 shows the engineering stress strain diagram of the steel after fully austenitized at 880ºC followed by bainitic holding between 350-480ºC. The mechanical properties of the steel have been summarized in Table 3 and the change in the properties has been shown in Figure 6. Unlike inter critical annealing the ultimate tensile strength has been increased with a drastic decrease in the total elongation of the steel with increase in bainitic holding temperature with no significant variation in the yield strength. The best properties achieved in the fully austenitized condition followed by the lowest bainitic holding temperature of 350ºC with the yield strength>620MPa, UTS>1100MPa and TE>22% with the yield ratio >0.55 and UTS*TE>24.5GPa.% qualifying for the third generation AHSS.

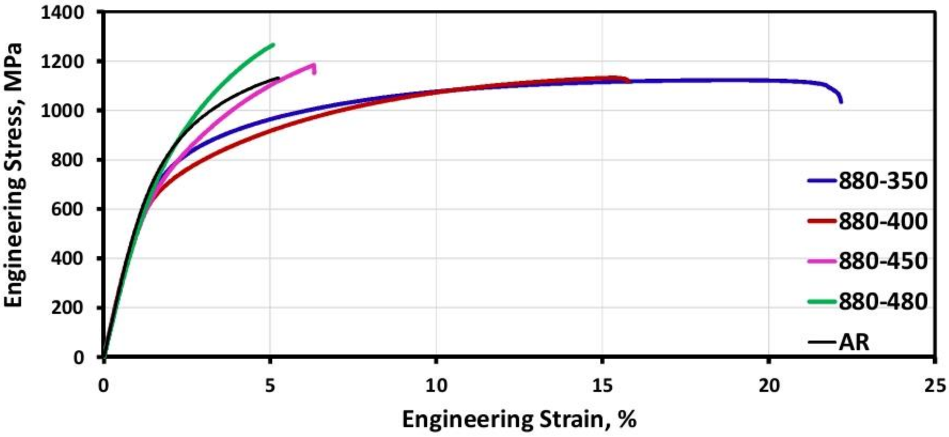

Figure 5. Engineering stress-strain diagram of the fully austenitized followed by bainitic holding steel

Table 3. Mechanical properties in austenitization above A_3 followed by bainitic holding

Austempering Temp. ºC	Austenitization Temperature- 880ºC					
	YS, MPa	UTS, MPa	TE, %	YR	UTS*TE, GPa.%	Hv0.5
350	625	1115	22.20	0.56	24.76	375
400	561	1126	15.42	0.50	17.37	404
450	562	1107	5.25	0.51	5.89	387
480	604	1273	5.21	0.47	6.63	389

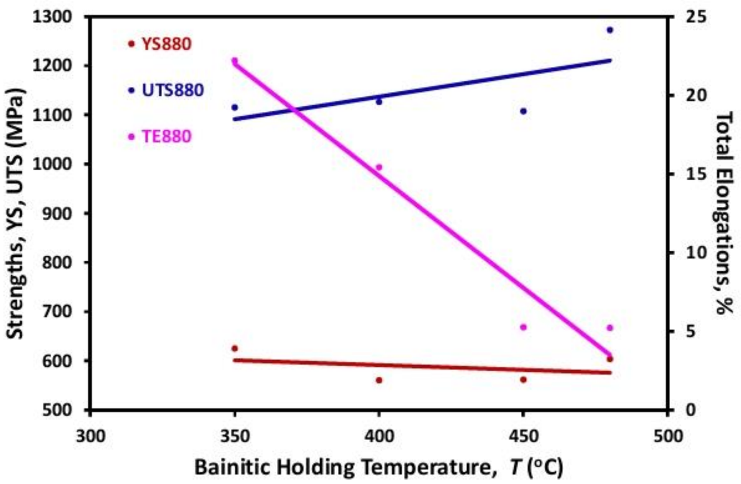

Figure 6. Change in YS, UTS, TE of the fully austenitized steel followed by bainitic holding

3.3 Microstructure

Optical microstructure and SEM micrograph of the hot deformed steel is shown in Figure 7 (a) & (b) respectively. The steel shows bainitic/martensitic microstructure with the interfaces of the plates/laths are very sharp resulted in the lower ductility of the steel although the strength of the steel is very high (>1100MPa).

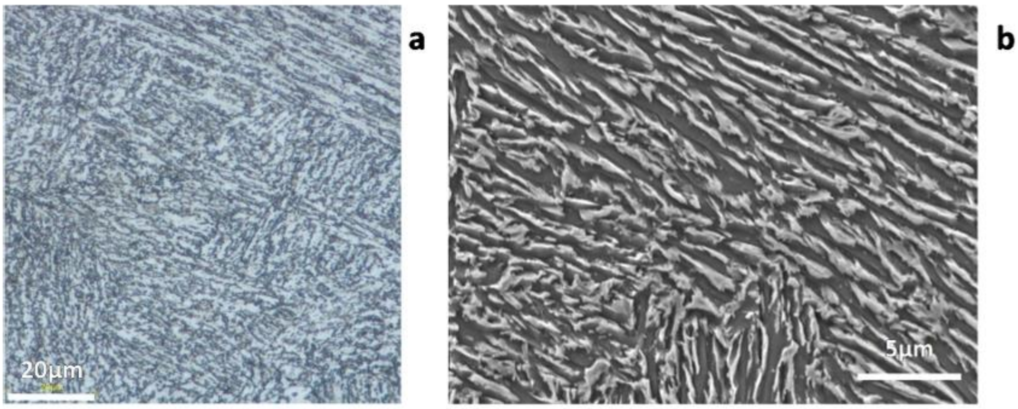

Figure 7. (a) Optical microstructure and (b) SEM micrograph of as-forged Steel

The optical microstructure and SEM micrograph as of the steel inter critical annealed at 800^{o}C followed by bainitic holding at 350, 400, 450 and 480^{o}C and water quenched is shown in Figure 8 (a)–(d) and (e)-(h) respectively. With the inter critical annealing at 800^{o}C lead to introduction of 30% ferrite and in the steel followed by bainitic holding at 350^{o}C forms lower bainite and tempered structure of the pre-existing bainite/martensite which improves the ductility of the steel above 15%. With the increase in bainitic holding temperature the structure changes from lower bainite to upper bainite with the coarser structure of the lath/plate of the bainites. However, the elongation does not drop much due to both the presence of 30% ferrite and coarsening of the bainite lath/plate structure. The yield strength of the steel decreased with the increase in bainitic holding temperature due to the tempered structure of the pre-existing bainite/martensite.

The optical microstructure and SEM micrograph as of the steel inter critical annealed at 880^{o}C followed by bainitic holding at 350, 400, 450 and 480^{o}C and water quenched is shown in Figure 9 (a)-(d) and (e)-(h) respectively. The steel subjected to bainitic holding at 350 and 400^{o}C shows globular type bainite with a fully bainitic ferrite matrix to show lower bainite of the steel. The bainite content is found to be between 50-55% at 350^{o}C bainitic holding and between 60-65% at 400^{o}C bainitic holding. With further increase in the bainitic holding temperature the globular type bainites are transformed to lath/plate type upper bainites. The strength and elongations were greater than 1100MPa strength and >15% elongations at 400^{o}C bainitic holding, with the best properties at 350^{o}C with YS>620MPa, UTS>1100MPa and TE>22% with the YR>0.55 and UTS*TE>22.5 GPa.%. With further increase in the bainitic holding temperature the volume fraction of globular type bainites increased to increase the UTS and decrease the total elongation. With further increase in the bainitic holding temperature the upper bainites were formed with the lath/plate structure with their coarsening leading to poor elongation of the steel.

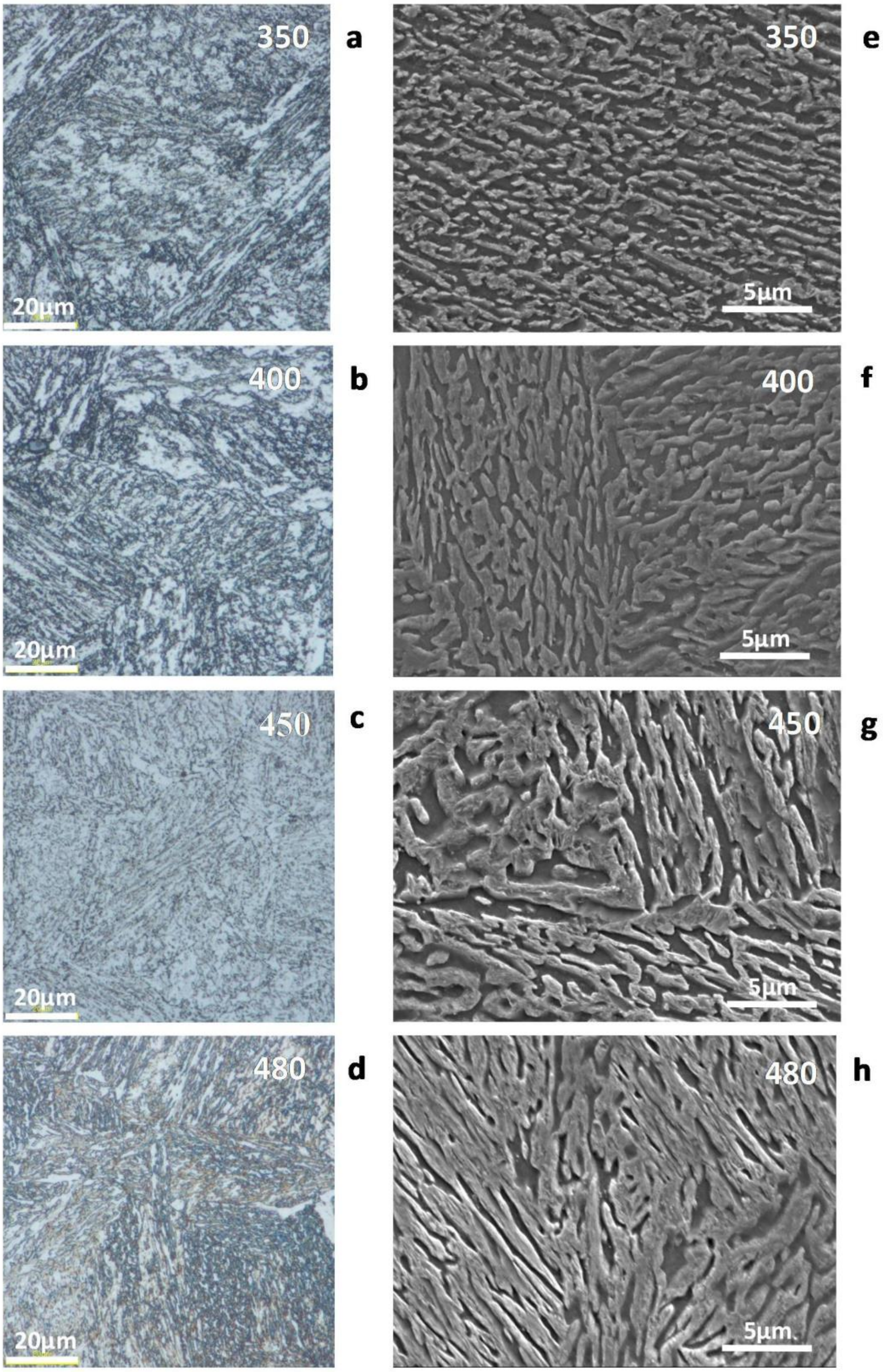

Figure 8. (a)- (d) Optical microstructure and (e)-(h) SEM micrograph of the steel IC annealed at 800ºC/5min followed by bainitic holding at 350, 400, 450 and 480ºC/5min respectively followed by WQ

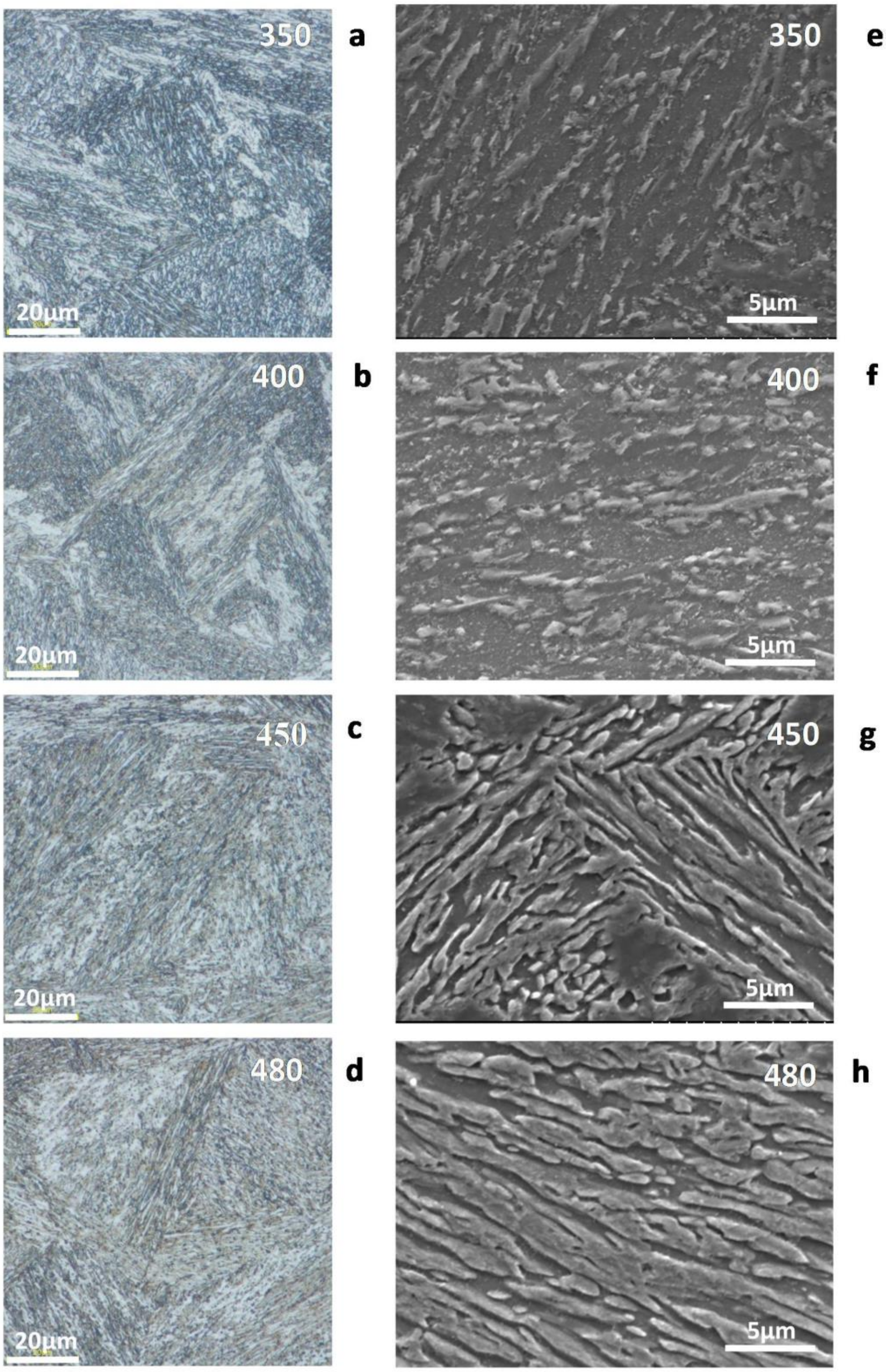

Figure 9. (a)- (d) Optical microstructure and (e)-(h) SEM micrograph of the steel austenitized at 880°C/5min followed by bainitic holding at 350, 400, 450 and 480°C/5min respectively followed by WQ

3.4 Phase Fraction/Retained Austenite Through XRD

XRD of the as-received (AR) and at selected bainitic held samples is shown in Figure 10. The retained austenite (RA) of the steel at selected bainitic holding conditions are summarized in Table 4. It can be observed that the RA is abound 4.3% at the condition of inter critical annealing followed by bainitic holding at 350°C. Such bainite gives the TRIP effect to give the better strength-ductility to the steel. With increase in bainitic holding temperature the RA is getting transformed to fully bainitic structure resulting in proving reasonable strength and ductility to the steel. In the case of fully austenitized condition followed by bainitic holding at 350 and 400°C the

RA is around 10-12% which gives very good strength elongation due to the TRIP effect. After that the RA transformed to bainitic structure/ martensitic structure resulting in poor ductility of the steel.

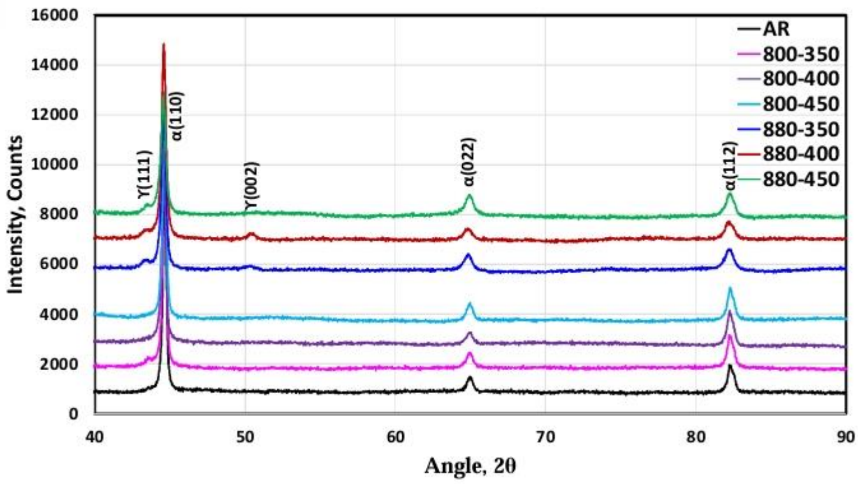

Figure 10. XRD of the as-received (AR) steel and bainitic holding in the temperature range of 350-480oC for 5min after austenitized at 800 and 880ºC for 5min

Table 4. Retained austenite of the steel evaluated through XRD

Austenitization Condition	Bainitic Holding Condition	Retained Austenite, %
Inter-Critical Austenitization 800ºC/5min (70% austenite)	350ºC/5min/WQ	4.30
	400ºC/5min/WQ	0
	450ºC/5min/WQ	0
Fully Austenitization (100% austenite)	350ºC/5min/WQ	10.16
	400ºC/5min/WQ	12.17
	450ºC/5min/WQ	4.38

4. Conclusions

A steel of composition (wt. %) 0.2C-1.7%Si-2%Mn-0.9%Cr-0.2%C-0.18%Mo-0.07Nb-0.04Ti was developed in the present study and optimized its heat treatment cycle to achieve the best level of mechanical properties by bainitic holding in a salt bath.

The steel formed is a carbide free bainite with the yield strength > 600MPa, ultra high tensile strength >1100MPa and TE>20% to give the yield ratio >0.55 and the product of UTS and TE >22 GPa.% to give the third generation AHSS properties for the optimised heat treatment condition (austenitization at 880ºC/5min-salt bath bainitic holding at 350ºC/5min/WQ to give globular type bainites in the range of 50-55% and 10% retained austenite which provides TRIP effect). Presence of fine precipitates of micro alloying further improves the strength of the steel by grain refinement and dislocation pinning.

References

Adam Skowronek, Erick C-Tapia, Pilar T-Balsera, C G-Mateo, Jose AJimenez, Roumen Petrov, Adam Grajcar, (2022). Bainite plate thickness reduction and microstructure tailoring by double austempering of Al-rich 3Mn steel. *Materials Science and Engineering: A*, 853, 143743.

Avanish Kumar, Aparna Singh, (2021). Mechanical properties of nanostructured bainitic steels. *Materialia*, *55*, 101034.

C P Luo, Jiangwen Liu, (2006). Crystallography of lath martensite and lower bainite in alloy steels. *Materials Science and Engineering A*, *438*, 149-152. DOI: 10.1016/j.msea.2005.12.046.

Chengjia Shang, Xinlai He, Huaxin Hou, (2010). The Development of High Performance Low Carbon Bainitic Steel, Niobium nearing structural steels. Edited by Steven G. Jansto and Jitendra Patel, *TMS (The Mineral, Metals and Materials Society)*.

David De-Castro, Adriana Eres-Castellanos, Javier Vivas, F G. Caballero, David SanMartín, Carlos Capdevila, (2022). Morphological and crystallographic features of granular and lath-like bainite in a low carbon microalloyed steel. *Materials Characterization*, *184*, 111703.

E. Jezierska, J. Dworecka, K. Rozniatowski, (2014). Nanobainitic Structure Recognition and characterization using transmission electron microscopy. *Archives of Metallurgy and Materials*, *59*(4), 1633-1636. DOI: 10.2478/amm-2014-0277.

F G Caballero, H K D H Bhadeshia, K J A Mawella, D G Jones and P Brown, (2001). Design of novel high strength bainitic steels: Part 1. *Materials Science and Technology*, *17*, 512-516.

F G Caballero, M J Santofimia, Carlos Capdevila, Carlos Garcia-Mateo and Carlos Garcia De Andres, (2006). Design of Advanced Bainitic Steels by Optimisation of TTT Diagrams and T_0 Curves. *ISIJ International*, *46*(10), 1479-1488.

F.G. Caballero, (2012). Carbide-free bainite in steels, Phase Transformations in Steels Fundamentals and Diffusion-Controlled Transformations. *Woodhead Publishing Series in Metals and Surface Engineering*, *1*, 436-467.

G. Spanos, H.S. Fang & H.I. Aaronson, (1990). A mechanism for the formation of lower bainite. *Metallurgical Transactions A*, 21, 1381-1390.

Gopal Sanyal, (2023). Trip-Aided Bainitic Ferrite or Carbide-Free Bainite (CFB) Steel: a Revisit. *Modern Approaches on Material Science*. DOI: 10.32474/MAMS.2023.05.000211.

H.K.D.H. Bhadeshia, (1980). The lower bainite transformation and the significance of carbide precipitation. *Acta Metallurgica*, *28*(8), 1103-1114.

Jianhao Yan, Xianguang Zhang, Huan Liu, Goro Miyamoto, Zhanmin Cao, Yongjie Z hang, Yiwu Pei, Peng Shi, Jiajun Chen, Tadashi Furuhara, (2024). Enhancing ductility of the TRIP aided bainitic ferrite steel by Mn heterogeneity introduced via reversion: Towards the 3rd generation. *Scripta Materialia*, *252*(1), 116241.

K. Hausmann, D. Krizan, A. Pichler, E. Werner, (2013, October). TRIP-aided bainitic-ferritic sheet steel: a critical assessment of alloy design and heat treatment, Conference Paper, https://www.researchgate.net/publication/259841165.

Lucia Morales-Rivas, (2022). Viewpoints on Technological Aspects of Advanced High Strength Bainitic Steels. *Metals*, *12*, 195. https://doi.org/10.3390/met12020195

P. Retzl, E. Kozeschnik, (2024). The tale of upper and lower bainite: A computational analysis of concurrent C-diffusion and precipitation. *Scripta Materialia*, *248*, 116146.

R. M. Jentner, S. P. Tsai, A. Welle, S. Scholl, K. Srivastava, J. P. Best, C. Kirchlechner, G. Dehm, (2023). Automated classification of granular bainite and polygonal ferrite by electron backscatter diffraction verified through local structural and mechanical analyses. *Journal of Materials Research*, DOI:10.1557/s43578-023-01113-7.

Radhakanta Rana, Erick Cordova-Tapia, Jose A. Jimenez, Lucia Morales-Rivas and Carlos Garcia-Mateo, (2024). Design of carbide free bainitic steels for hot rolling practices. *Philosophical Magazine Letters*, *104*(1), 2322552. https://doi.org/10.1080/09500839.2024.2322552.

T. Furuhara, H. Kawata, S. Morito, T. Maki, (2006). Crystallography of upper bainite in Fe– Ni–C alloys. *Materials Science and Engineering: A*, *431*(1-2), 228-236.

V. C. Igwemezie, P. C. Agu, (2014). Development of Bainitic Steels for Engineering Applications. *International Journal of Engineering Research & Technology (IJERT)*, *3*(2), 2698-2711.

X.F. Yu, Y.H. Wei, D.Y. Zheng, X.Y. Shen, Y. Su, Y.Z. Xia, Y.B. Liu, (2022). Effect of nano-bainite microstructure and residual stress on friction properties of M50 bearing steel. *Tribology International*, *165*, 107285.

Z.X. Qiao, Y.C. Liu, L.M. Yu, Z.M. Gao, (2009). Formation mechanism of granular bainite in a 30CrNi3MoV steel. *Journal of Alloys and Compounds*, *475*(1-2), 560-564. https://doi.org/10.1016/j.jallcom.2008.07.110.

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The Interpersonal Whole Brain Model of Care™: Utilizing the Union of Science & Love to Meet the Needs of Neurodivergent Populations

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Abstract

The Interpersonal Whole Brain Model of Care™ (IWBMC™) addresses the increasing prevalence of neurodevelopmental disorders through an innovative blend of science and compassionate care. Developed by Amy O'Dell and applied at Jacob's Ladder School, this model includes seven interconnected elements: Spirit & Will, Neurodevelopmental Methodology, Learning Style, Emotional-Relational-Behavioral Assessments, Physiological Factors, Social Structure, and Whole Person Integration. Rooted in interpersonal neurobiology and positive psychology, the IWBMC™ formulates personalized care plans within a therapeutic ecosystem anchored by hope, truth, and love, recognizing each client not merely as their diagnosis but as "a soul ready to be cared for."

Keywords: neurodiversity, interpersonal neurobiology, whole-brain approach, therapeutic relationship, personalized intervention, neuroplasticity, neurodevelopmental disorders, holistic care

1. Understanding the Rise in Neurodiversity & the Challenges for the 21st Century

More attention has been drawn to the rise in neurodevelopmental disorder diagnoses over the past decade. Disorders like Attention Deficit Hyperactivity Disorder (ADHD) and Autism Spectrum Disorder (ASD) have notably increased (Yang et al., 2023; Abdelnour, Jansen, & Gold, 2022). The prevalence of neurodevelopmental disorders, particularly ASD, has significantly increased, with current data from the Centers for Disease Control and Prevention indicating that 1 in 36 children are now diagnosed with ASD (Maenner, 2023). This change represents a striking 432% rise in ASD diagnoses over the past two decades. Neurodevelopmental disorders, including ASD, ADHD, and others, are complex conditions characterized by a diverse range of symptoms that vary significantly in nature and severity among individuals (Goldberg, 2023).

The interventions for neurodevelopmental disorders should be diverse to match the disorders' diversity. However, few studies look at an integrated approach to intervention for neurodevelopmental disorders despite evidence suggesting its value (Siegel & Drulis, 2023). According to Siegel's interpersonal neurobiology perspective, change occurs in relation to another person, making relational quality critical. Researchers also suggest that interventions combining multiple approaches can reduce symptoms of various neurodevelopmental disorders, including autism. Current research indicates that person-centered, humanistic, or positive psychological approaches are necessary (Chapman & Botha, 2023). In fact, co-creating treatments and interventions with neurodivergent individuals has been highly successful due to the established connections between families and providers (Schwartzman et al., 2024). These interventions can reduce negative social and emotional behaviors associated with these conditions (Kostopoulos et al., 2021).

Some researchers also suggest that since we have validated several interventions for neurodevelopmental disorders, the next step is to develop individualized programming that utilizes several approaches at once rather than solely one approach (Hume et al., 2021). Specifically, Hume and colleagues state: “Practitioners [should] establish programs with strong program quality as a foundation, develop individualized and clearly articulated goals for children/youth, select and implement practices that may have different theoretical bases but also have demonstrated efficacy” (p. 4029). In essence, there is a need to develop programs that incorporate evidence-based practices and prioritize establishing solid client-provider relationships. These integrated programs and their outcomes for individuals with neurodevelopmental disorders should be rigorously studied to assess their effectiveness and potential for broader implementation. The Interpersonal Whole Brain Model of Care® (IWBMC™) seeks to harness evidence from existing practices to implement a model of care that meets the needs of neurodivergent individuals.

2. Outlining the IWBMC™

The Interpersonal Whole Brain Model of Care® is not just another therapeutic approach. It is a unique and innovative model founded on the principle of interconnectedness between body, mind, and soul (Siegel, 2023; Thompson, 2021). Founded by Amy O’Dell, the model recognizes that individuals have unique functional processes. It posits that despite differential or divergent developmental pathways, learning and change can occur when guided by trained, compassionate professionals. These concepts recognize that humans are inherently designed for connection, reflecting our neurological makeup. The model also posits that optimal brain function occurs when full connectivity is achieved, particularly between the left and right hemispheres. This holistic view of human functioning forms the cornerstone of the IWBMC™ approach — caring for the whole person.

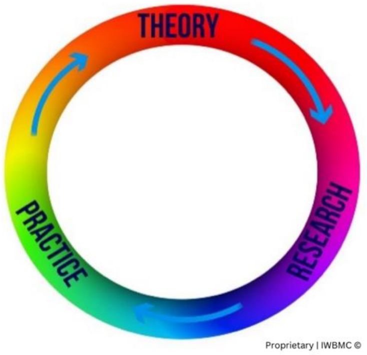

Figure 1. Theory, Research, Practice Wheel

The innovation of the IWBMC™ is currently embodied at the Jacob’s Ladder School and is intrinsically tied to the brain’s plasticity. Often, there is difficulty connecting theory to research and practice, although all are required to create successful interventions (see Figure 1). Few institutions genuinely align their beliefs with their practices seamlessly. O’Dell has successfully parsed the existing theory and research within educational neuroscience, developmental psychology, and cognitive psychology to develop the ideas and interventions grounding the IWBMC™. This seamless connection allows for delivering care that offers clients the best strategies.

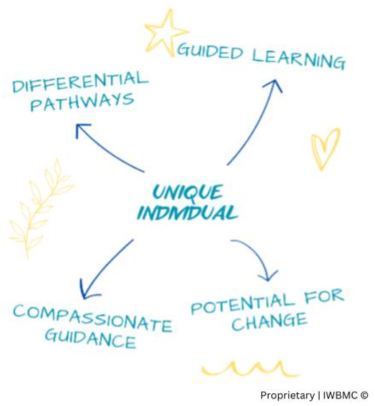

Figure 2. Understanding the Individual & the IWBMC™

In essence, the IWBMC™ embodies plasticity, mirroring the brain's adaptability. Acknowledging that science has demonstrated the brain's capacity for change, those working with clients whose brains developed along differential pathways or endured trauma must operate with a similarly flexible mindset. Each client is distinct, necessitating creativity and adaptability while maintaining a consistent care framework.

Within the IWBMC™, flexibility and creativity are not just abstract concepts. They are anchored by an unwavering commitment to service excellence and an unconditional love for every client. Providers and administrators hold steadfast hope for the families they engage with, believing in each client's potential for growth and improvement. O'Dell emphasizes the importance of adhering to each client's developed plan while remaining open to necessary adjustments. By looking beyond diagnoses and conventional approaches, providers expand their understanding of each client's unique potential, refusing to be limited by labels or traditional paradigms.

3. Components of the IWBMC™

A distinctive feature of the IWBMC™ is its innovative fusion of scientific understanding with the power of love, termed "the union of science and love." This integration acknowledges that effective healing and personal growth require empirical knowledge and deep emotional connection. The model recognizes that love, in its essence, is a form of connection and that our physiological and psychological systems are primed to seek and benefit from such connections. Within the IWBMC™ framework, establishing meaningful bonds is crucial for facilitating developmental progress and healing processes, simultaneously recognizing that all elements must be considered in relation to the others rather than viewed in isolation.

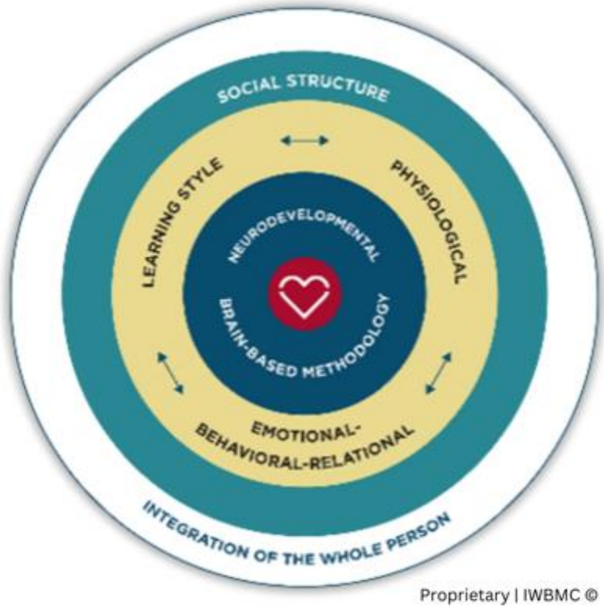

Figure 3. Diagram of the Interpersonal Whole-Brain Model of Care®

The Interpersonal Whole-Brain Model of Care® (IWBMC™) is the culmination of Amy O'Dell's three decades of work with individuals facing neurodevelopmental challenges. This comprehensive model integrates theory and evidence-based strategies to create personalized treatment plans. The IWBMC™, as illustrated in Figure 3, comprises seven key elements: Spirit & Will, Neurodevelopmental Brain-based Methodology, Learning Style, Emotional-Relational-Behavioral Assessments, Physiological, Social Structure, and Integration of the Whole Person. Each component is outlined below.

1) **Spirit & Will.** The core identity and functioning of the client are referred to as Spirit and Will in the model of care. According to O'Dell, this is the driving force for change and is considered the center of the model of care. If a client's spirit and will are crushed, the model must address this issue before proceeding with any other intervention. Research shows that spirit and will are crucial for change. Positive psychologist Martin Seligman emphasized the significance of learned hopelessness in hindering achievement (1972). When someone experiences constant failure, they start seeing themselves as a failure, and failure becomes their identity. Susan Harter's work on self-concept supports Seligman's theory, indicating that self-esteem and efficacy are connected to feelings of accomplishment (2008).

When many clients come to Jacob's Ladder School, they (and their families) feel defeated because they have had many negative experiences. However, Jacob's Ladder uses the IWBMC™ to shift perspective and provide hope for clients. In that way, the model of care seeks to build on each client's strengths while also developing the client's spirit and will. Every client is unique, so everyone has their own spirit and will. As such, the interventions are targeted not just to meet root problems but also to accommodate and address the nature of the individual — their personality, motivations, and characteristics.

2) **Neurodevelopmental.** The second component of the IWBMC™ involves using a neurodevelopmental methodology to understand and treat clients. As mentioned earlier, a person is made up of a mind, body, and soul. Therefore, it is crucial to understand the brain and its functioning in order to help improve the functioning of our clients with neurodevelopmental disorders. O'Dell emphasizes the importance of determining the under and over-connectivity of neural networks in clients' brains, which is a unique aspect of this methodology. This part of the IWBMC™ focuses on testing clients using the QEEG and a set of assessments covering everything from interhemispheric communication to vestibular functioning and sensory processing. The underlying idea is that the brain is plastic and flexible, and in order to understand each client's unique challenges, it is necessary to have a comprehensive understanding of their brain processing.
3) **Learning Style:** Learning style is crucial in tailoring interventions to each client. Clients' learning styles are assessed to uncover potential challenges and strengths. This assessment provides invaluable insights into how clients process and retain new information, what drives their achievement motivation, and the intricacies of their learning processes. In addition, cognitive aspects are evaluated, including sequential processing and working memory levels. By understanding a client's unique learning style, academic readiness, abilities, and level of independence, we craft genuinely personalized intervention plans. This approach ensures that new information is presented in a way that resonates with the client, maximizing retention and fostering a sense of accomplishment.

The interventions are designed to adapt to these individual learning styles, creating an environment where clients can thrive. Whether a client learns best through visual aids, hands-on experiences, or abstract concepts, we incorporate these preferences into our strategies. This tailored approach enhances learning outcomes and boosts the client's confidence and engagement in the learning process.

4) **Physiological:** Recently, we have gained a deeper appreciation for how nutrition and other physiological elements impact our overall well-being (Bray, 2019). Sleep and cardiovascular health have emerged as crucial factors in growth and development. It has become increasingly clear that physiological health, brain development, and functioning are an intricate connection. At Jacob's Ladder, we recognize the importance of understanding each client's unique physiological needs. This includes their diet, exercise routines, medication requirements, and how these factors influence their brain processing and development.

This holistic approach allows for developing intervention plans that address the clients' cognitive needs and the fundamental physiological foundations that support optimal brain function. This comprehensive strategy ensures that we nurture body and mind, setting the stage for more effective and lasting progress in our clients' development.

5) **Emotional-Behavioral-Relational:** One of the most critical components of this model is the recognition of a client's emotional, behavioral, and relational strengths and challenges. Approaches to learning, interaction with others, and overall mindset can be linked to a client's emotional, behavioral, and relational strengths and areas for improvement. Incorporating strengths into client programming helps establish a positive therapeutic relationship between the client and the provider. Additionally, O'Dell has developed the IWBMC™ Trauma Support Model that acknowledges the trauma histories of clients and seeks to address those issues as part of the overall plan for the client.
6) **Social Structure:** The client's external support systems can be critical to understanding how they move through their programming. Learning does not stop when the client's day finishes. External social support systems are needed to partner with Jacob's Ladder to reinforce learning at home. In addition, occupational therapists, physical therapists, or speech-language pathologists may be working with a client on a particular behavior or way of functioning within and outside of regular clinical hours to support families. There are external influences on our lives and development. The social support here is internal (through our providers) and external (through our work with families). However, the strength of the work at JL is in creating a community of hope. This interdependence is critical to understanding how to support clients as they move through the programs. Daniel Siegel calls it "interpersonal neurobiology" (2022, p. 61). We are connected

through our neurobiological core, and this is a strength that allows us to support our clients. Both Hannaford's work and Jacob's Ladder's approach are grounded in caring for the whole person within a community context. Hannaford references the African concept of ubuntu: "Because I am, we are; and because we are, I am" (2007, p. 229), highlighting the power of interconnectedness in fostering belonging and finding solutions.

7) **Integration of the Whole Person:** The methodology prioritizes a whole-person and whole-brain approach to foster integration. O'Dell characterizes this as a "whole-person, whole-brain" approach, acknowledging that human development does not occur in isolation. Instead, it is influenced by various biological and environmental factors. The IWBMC™ embraces this perspective, aiming to develop an action plan that addresses the client's biological makeup (including spirit and will, neurobiology, physiological states, and cognitive deficits) and their environmental support systems.

At its core, the model is facilitated by a trained, empathetic provider who strives to create an optimal environment for growth and learning. This approach recognizes the complex interplay between an individual's internal characteristics and their external surroundings, offering a holistic framework for addressing neurodevelopmental challenges.

Considering biological and environmental factors, the IWBMC™ provides a comprehensive strategy for supporting individuals with neurodevelopmental differences. This model represents a significant step forward in personalizing care and maximizing potential for growth and development.

4. Theoretical Depth and Practical Application

The Interpersonal Whole-Brain Model of Care® is based on interconnected theoretical principles, with relationship and connection as crucial aspects. Recent literature has extensively explored the impact of the therapeutic relationship with individuals, noting the critical role of establishing a connection with clients (see Siegel, Schore, & Cozolino, 2021; Gilbert, 2009). Both Siegel and Gilbert discuss the importance of understanding the intersubjectivity of therapeutic work and emphasize that change is made by establishing a safe, compassionate relationship with the client. The IWBMC™, with the underlying approach of hope, truth, and love, draws on these theoretical concepts to establish a safe environment for clients, reducing shame that may have been associated with their previous environment and offering a space for clients to grow and change. This empathetic relationship allows providers to adjust strategies as they work with clients to meet immediate needs and ensure that clients are working at their challenge point.

Each element of the IWBMC™ is grounded in broader psychological and neuroscientific principles and evidence-based practices. The model's emphasis on spirit and will draws support from Susan Harter's theories on self-esteem, efficacy, and sense of belonging (2008). Harter posits that this approach aligns with the fundamental human need for belonging, further reinforced by Martin Seligman's theories of positive psychology and health (1999, 2008). Seligman also introduces the notion of a strengths-based approach rather than a deficit-driven approach. While the IWBMC™ assesses for areas of deficiency, the model builds on the strengths of the individual's spirit, will, and learning styles to help drive change.

Additionally, Angela Duckworth's concept of grit (2007) and Carol Dweck's (2006) work on growth mindset contribute to this model aspect that speaks to the notion that effort and hard work can drive change. The client and the provider embrace growth mindsets and demonstrate grit throughout the process. This means they consistently put forth effort in the learning processes and interventions. The shared commitment to perseverance is crucial, enabling both parties to navigate challenges, maintain motivation, and work towards continuous improvement. This approach recognizes that progress often requires sustained effort and resilience from both the client and the provider, creating a collaborative environment conducive to meaningful growth and development.

The neurodevelopmental perspective of the IWBMC™ is rooted in the work of Daniel Siegel (2021) and Carla Hannaford (1995). This component is also central to Uri Bronfenbrenner's (1979) ecological systems theory, which supports the IWBMC™'s strategy of connecting the work done at the neurodevelopmental center with providers to create wraparound services involving parents. O'Dell notes that the work is grounded in scientific principles. Still, clients need their providers and the support of their families since the learning process flows between home and school.

The IWBMC™'s approach to understanding learning styles is informed by Howard Gardner's theories of intelligence and schooling (2011), Vygotsky's sociocultural theories (1978), which emphasize the importance of a teacher or guide, and Bruner's idea of scaffolding the learning process (1976). These frameworks help tailor interventions to individual cognitive strengths and preferences.

Recognizing physiological challenges within the IWBMC™ draws on research in sensory integration and points again to work in interpersonal neurobiology, acknowledging the profound impact of physical states on cognitive and emotional functioning (Hannaford, 1995). The model's attention to emotional and behavioral challenges is supported by theories of emotional intelligence and regulation and cognitive-behavioral approaches to managing behavior (Goleman, 1995).

5. Grounding the IWBMC™: The Importance of Hope, Truth, Love

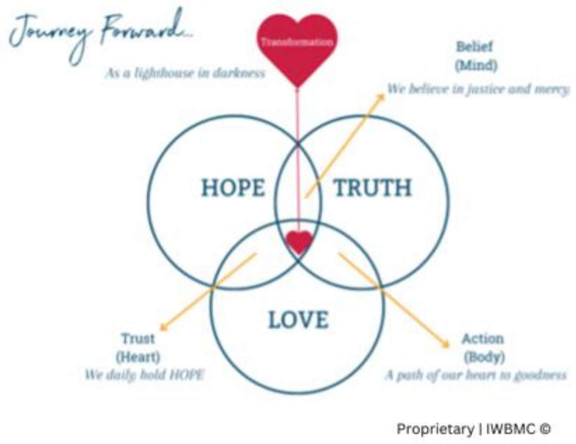

Figure 4. The Hope, Truth, Love Model

The IWBMC™ is bound by the principles of truth, hope, and love (see Figure 4). Those implementing the model **maintain honesty (truth) about their clients' limitations and capabilities, avoiding overpromising**. A key focus is working with clients based on a plan developed through careful attention to evidence from thorough testing. As O'Dell states, the process creates a unique "neurological fingerprint" for the client. This *thumbprint*, once identified, leads to a comprehensive therapeutic educational plan, considering each unique aspect of the individual. While the truth of the situation is presented to families, **the plan embodies the hope that change—even incremental—is possible**. Binding this together is a **sacrificial love experienced through the therapeutic relationship**.

From a neurological standpoint alone, over- and under-connectivity patterns in the brain dictate much of a person's social, emotional, and cognitive output. Identifying these patterns as one aspect of over 1,300 variables leads to a nonrepeatable way forward through challenges—whether they be emotional, behavioral, learning challenges and differences, or rehabilitative from an event or rare genetic syndrome.

The IWBMC™ develops individualized plans incorporating varied interventions—from movement to whole-word language models to counseling. The model is based on the belief that every child has the innate desire to learn and to do well. Through wraparound services, dedicated providers build rapport with clients and their support network (e.g., family and caregivers) to support each individual's plan. The principle of hope drives the development of interventions specified for each learner. This comprehensive and personalized approach aims to address each client's unique needs, fostering an environment where growth and progress are not just possible but expected.

The IWBMC™ places significant emphasis on environmental factors in therapeutic and developmental contexts. Great care is taken to create a nurturing, secure community atmosphere that mirrors ideal early developmental conditions. This approach extends beyond client care to comprehensive staff training, fostering a culture that fully embodies the principles of the IWBMC™. Central to this culture is the commitment to authentic interactions at all levels. Every community aspect—from decision-making processes to interpersonal communications—is meticulously aligned to build a supportive and growth-oriented environment.

6. Creating a Therapeutic Ecosystem

Within the IWBMC™ framework, truthfulness is considered essential for developing genuine connections. The therapeutic environment at Jacob's Ladder is designed to encourage honesty, vulnerability, and sincere engagement among all community members. This focus on authenticity, which deeply values and respects each individual's unique journey, creates a safe and nurturing space conducive to personal growth, healing, and transformation—all key objectives of the IWBMC™.

The model is built upon three interconnected core principles: hope, truth, and love. These elements have broad applications extending far beyond the immediate therapeutic context, influencing every aspect of the Jacob's Ladder community. By integrating these principles, the IWBMC™ creates a comprehensive approach to community building that supports clients' development and nurtures staff members' growth and well-being. The result is a dynamic, symbiotic ecosystem where mutual growth and care are continually fostered, embodying the holistic spirit of the IWBMC™ and setting a new standard for therapeutic interventions.

The IWBMC™ was developed to understand how clients learn, aiming to eliminate barriers to success. All individuals should be treated with respect and dignity in their learning journey. A client is not their diagnosis. They are a soul ready to be cared for. The lens of the IWBMC™ expects clients to see their full potential through their loving environment—whatever that may be for that individual.

7. Innovation and Continuous Evolution

The IWBMC™ is not a static model but a dynamic, evolving approach. O'Dell's vision encourages ongoing research and innovation. This might involve collaborations with universities, participation in neuroscience studies, or the development of new therapeutic technologies. The model's flexibility allows for the rapid integration of new findings and techniques, ensuring that clients always benefit from the most current and effective interventions.

In conclusion, the IWBMC™ represents a holistic, scientifically grounded, and deeply compassionate approach to therapeutic care. Its comprehensive nature, grounding in neuroplasticity, and emphasis on individualized, whole-person care set a new standard in the field of neurodevelopmental therapy and education. Through its implementation at Jacob's Ladder and beyond, the IWBMC™ continues to evolve, pushing the boundaries of what is possible in therapeutic interventions and offering hope and transformation to individuals and families facing neurodevelopmental challenges.

Disclaimer: *The use of the IWBMC™ does not substitute the expertise of physical, speech, or occupational therapists (or other related specialties). Instead, it incorporates elements emphasizing whole-brain health and stimulation, continuous development, adaptive fitness, nutrition, and educational achievement. We strongly advocate collaboration with other professionals to deliver comprehensive care for individuals with unique needs.*

References

Abdelnour, E., Jansen, M. O., & Gold, J. A., (2022). ADHD diagnostic trends: increased recognition or overdiagnosis? *Missouri medicine*, *119*(5), 467.

Bronfenbrenner, U., (1979). Contexts of child rearing: Problems and prospects. *American psychologist*, *34*(10), 844.

Bruner, J. S., (2006). *In search of pedagogy volume I: The selected works of Jerome Bruner, 1957-1978*. Routledge.

Chapman, R., & Botha, M., (2023). Neurodivergence-informed therapy. *Developmental Medicine & Child Neurology*, *65*(3), 310-317.

Duckworth, A. L., Peterson, C., Matthews, M. D., & Kelly, D. R., (2007). Grit: perseverance and passion for long-term goals. *Journal of personality and social psychology*, *92*(6), 1087.

Dweck, C. S., (2006). *Mindset: The new psychology of success*. Random House.

Gardner, H. E., (2011). *Frames of mind: The theory of multiple intelligences*. Basic books.

Goldberg, H., (2023). Unraveling neurodiversity: Insights from neuroscientific perspectives. *Encyclopedia*, *3*(3), 972-980.

Goleman, D.J., (1995). Emotional Intelligence: Why It Can Matter More Than IQ.

Hannaford, C., (2013). *The Dominance Factor: How Knowing Your Dominant Eye, Ear, Brain, Hand and Foot Can Improve Your Learning*. Arlington, VA: Great Ocean Publishers.

Harter, S., (2013). The development of self-esteem. In *Self-esteem issues and answers* (pp. 144-150). Psychology Press.

Hume, K., Steinbrenner, J. R., Odom, S. L., Morin, K. L., Nowell, S. W., Tomaszewski, B., & Savage, M. N., (2021). Evidence-based practices for children, youth, and young adults with autism: Third generation review. *Journal of autism and developmental disorders*, 1-20.

Kotsopoulos, S.I., Karaivazoglou, K., Florou, I.S., Gyftogianni, M.I., Papadaki, E.J., & Kotsopoulou, A., (2021). Systematic Intervention for Children with Autism Spectrum Disorder and Integration in Regular School Classes: A Naturalistic Study. *Global Pediatric Health*, *8*.

Maenner, M. J., (2023). Prevalence and characteristics of autism spectrum disorder among children aged 8 years—Autism and Developmental Disabilities Monitoring Network, 11 sites, United States, 2020. *MMWR. Surveillance Summaries*, *72*.

Seligman, M. E., (1972). Learned helplessness. *Annual review of medicine*, *23*(1), 407-412.

Siegel, D. J., Schore, A. N., & Cozolino, L., (2021). *Interpersonal Neurobiology and Clinical Practice (Norton Series on Interpersonal Neurobiology)*. WW Norton & Company.

Siegel, D. J., (2022). *IntraConnected: MWe (Me+ We) as the Integration of Self, Identity, and Belonging (Norton Series on Interpersonal Neurobiology)*. WW Norton & Company.

Siegel, D. J., & Drulis, C., (2023). An interpersonal neurobiology perspective on the mind and mental health: personal, public, and planetary well-being. *Annals of General Psychiatry*, *22*(1), 5.

Schwartzman, J. M., Roth, M. C., Paterson, A. V., Jacobs, A. X., & Williams, Z. J., (2024). Community-guided, autism-adapted group cognitive behavioral therapy for depression in autistic youth (CBT-DAY): preliminary feasibility, acceptability, and efficacy. *Autism*, *28*(8), 1902-1918.

Vygotsky, L. S., (1978). Socio-cultural theory. *Mind in society*, *6*(3), 23-43.

Yang, L., Chen, F., He, X., Tong, Y., Li, Q., Yang, T., ... & Shi, Z., (2023). Global burden and inequality of autism spectrum disorders: Based on data from the 2019 Global Burden of Disease study. *Preventive Medicine Reports*, *36*, 102511.

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Hepatitis A Virus (HAV) Infection: A Prevention Strategy Through Hygienic Maintenance and Vaccination

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Abstract

Hepatitis is considered as the inflammation of the liver. Hepatitis A is a highly contagious liver damageable, but vaccine-preventable disease that is caused by the hepatitis A virus (HAV). It is transmitted through food and water by oral-fecal contact that is contaminated with the undetectable microscopic stool (feces, poop) of an infected person with HAV that are too small to be seen. This virus can be spread through the household or sexual contact with an infected person. It can survive for extended periods in the environment. It is one of the widespread viruses that cause hepatitis all around the globe. Younger children are asymptomatic, but infection symptoms begin to clearer among the adults. The disease is self-limited. Hepatitis A vaccine is developed in 1995 in the USA that may protect against disease for as long as 20 to 30 years. This study aims to prevent and treat the hepatitis A viral infection for reducing morbidity and mortality through the hygiene practice and vaccination in due time.

Keywords: Hepatitis A, vaccine, immune globulin

1. Introduction

Hepatitis A virus (HAV) infection is the most common form of acute viral hepatitis in the world that can damage the liver (Ambrosch et al., 2004). HAV is tissue or cell specific and attacks only the liver. It is generally mild and self-limiting with a typical recovery in two weeks (Gerardi & Zimmerman, 2005). HAV infection accounted for about half of all acute onset icteric illness and acute liver failure cases, and is associated with significant morbidity and mortality (Sood et al., 2019). The HAV is found worldwide. It can survive very well in the environment. It can alive on hands for several hours and in food at room temperature for much longer. It also can survive in food even after freezing. Humans are considered to be the only important reservoir of HAV, and there are no insect or animal vectors (Wasley et al., 2010).

It is highly endemic in developing nations due to overcrowding and poor sanitation, and is spread through contaminated food and water, where infection occurs in children asymptomatically. It is usually spread from one person to another through unsafe food or water, or through sexual contact (Aggarwal & Goel, 2015). But the levels of hygiene and sanitation in middle income countries are improving gradually. Consequently, the HAV contamination is decreasing among these countries (WHO, 2016). Symptoms of HAV are fatigue, fever, headache, muscle ache, nausea, joint stiffness, diarrhea, lack of appetite, and vomiting (FDA, 2012).

The risk factors related to HAV infections are people who use illicit drugs, men having sex with men, people who inject drugs, homeless people, etc. (James et al., 2009). At present there are two types of vaccines to prevent HAV: i) can adsorb onto an aluminium hydroxide adjuvant, and ii) contains formalin-inactivated hepatitis A particles (Beck et al., 2004). In the absence of vaccination most exposed neonates and young children will be infected and become lifelong carriers (Gow & Mutimer, 2001). As per global estimates of mortality, HAV infection ranked sixth amongst vaccine preventable infectious that causes of worldwide mortality (WHO, 2018).

From 1990 to 2019, the incidence rates of HAV infection have remained stable (Zeng et al., 2021). The World Health Organization (WHO) estimates that 1.5 million clinical cases of HAV are recorded per year with about 7,134 deaths in 2016. However, millions of HAV cases are recorded in underdeveloped countries (Savicka, 2022). During 2020, an estimated 19,900 people in the USA were infected with the HAV. Sometimes the life-threatening complications, such as fulminant hepatitis and hemolysis may develop with about 2% (Lednar et al., 1985). About 90% children have been infected with the HAV before the age of 10 years, most often without symptoms, and most of them live in low- and middle- income countries (Jacobsen & Wiersma, 2010).

2. Literature Review

The literature review is an introductory section of research that shows the works of previous researchers in the same field within the existing knowledge (Polit & Hungler, 2013). Emmet B. Keeffe and his coworkers have performed a study to compare the safety and immunogenicity of an inactivated hepatitis A vaccine in patients with chronic liver disease (CLD) with that in healthy subjects (Keeffe et al., 1998). F. Ambrosch and his coauthors have designed to assess the early antibody kinetics after a priming dose and the extent of the antibody increase after a booster dose of an inactivated virosomal HAV vaccine (Ambrosch et al., 2004).

Omid Gholizadeh and his coauthors want to examine the existing evidence for hepatitis A screening, diagnosis, and treatment. They have also discussed the structure of the HAV virus, the virus genome, how it is diagnosed, how it spreads, the importance of vaccination, and the factors derived from the HAV virus (Gholizadeh et al., 2023). Vikrant Sood and his coauthors have studied the HAV infection-related pediatric liver disease burden. They have observed that a significant proportion of subjects remain susceptible to HAV infection even after 10 years of age. They have suggested that population-based studies are required to further delineate the epidemiology of HAV infection in India for deciding introduction of HAV vaccine in the national immunization schedule (Sood et al., 2019).

Sofia Persson and her coworkers describe development and evaluation of a reverse transcription droplet digital PCR and reverse transcription real-time PCR (RT-qPCR) assay for detection of HAV in food and clinical specimens (Persson et al., 2021). Tauseef Ahmad and his coworkers have analyzed a bibliometric analysis to build an all-inclusive view of the status of research on HAV for facilitating researchers, health professionals, and policymakers to understand the characteristics of research output in this particular domain (Ahmad et al., 2021).

3. Research Methodology of the Study

Research is an essential device to the academicians for the leading in academic area (Pandey & Pandey, 2015). Researchers often write a methodology section with details of the research analysis (Kothari, 2008). Methodology provides the research design and analysis procedures to perform a good research (Hallberg, 2006). Research methodology shows the ways to the novel researchers for organizing, planning, designing and conducting a good research (Legesse, 2014).

The valuable information of our research is collected from the published and unpublished data sources (Mohajan, 2024a-e). In this paper, we have depended on the secondary data sources of hepatitis A virus (HAV), such as journal articles, books of famous authors, conference papers, internet, websites, etc. (Mohajan, 2017, 2018, 2020).

4. Objective of the Study

Main objective of this article is to discuss the aspects of liver disease that is developed by hepatitis A virus. The HAV attacks only the human liver and there is no other virus vector. It is not fatal as like other hepatitis viruses and death occurs rarely (WHO, 2013). Other minor objectives of the study are as follows:

1) to highlight the etiology and virology of HAV,

2) to focus on clinical presentation, symptoms and risk sites of the disease, and

3) to show the prevention strategy of HAV through the vaccination.

5. Etiology of HAV

Hepatitis A virus (HAV) is a frequent type of viral hepatitis. It was first isolated in 1979. It is an ultramicroscopic infectious parasitic agent that is not considered as living organism and can only replicate within the cells of living host human (Venes & Taber, 2013). It is a hepatotropic virus of the family Picornaviridae, genus Hepatovirus, containing a positive sense, linear, single-stranded RNA virus (a 27nm picornavirus) surrounded by a protein capsid that replicates in the liver, secreted in the bile, blood, and shed in stool (Heymann, 2008). It is able to survive in the low pH of stomach acid exiting the host through the biliary tract (Martin & Lemon, 2006). The virus is hardy, surviving on human hands and fomites, and requiring temperatures higher than 185ºF (85ºC) for inactivation (Kemmer & Miskovsky, 2000).

The incubation period of HAV is from 15 to 50 days, with an average of 25 to 30 days (Franco et al., 2012). HAV is a hydrophobic virus, environmentally hardy, and difficult to eliminate from contaminated surfaces (FDA, 2012). It can survive outside the body for months, depending on the environmental conditions, such as freezing, heat, chemical treatment (e.g., detergents and acids), and desiccation due to the absence of an envelope, but it is inactivated by formalin and chlorine. It also survives for extended periods in seawater, fresh water, wastewater, and soil (CDC, 2018).

6. HAV Virology

HAV is a tiny enteric virus with diameter 27-32nm (nanometers) that is a small, non-enveloped, unusual hepatotropic virus classified in the genus Hepatovirus within the family Picornaviridae (Figure 1). It is a positive-strand RNA genome that infects only primates (Enkirch et al., 2019). The genome of it is relatively short; approximately 7,500 nucleotides long (Kulsuptrakul et al., 2021). The 5′ ends of the RNA are physically attached to a viral genome-linked protein (VPg) or 3B and also lack a normal cap configuration and a brief untranslated section at the 3′ ends of the genome, which ends in a poly (A) tail (Gholizadeh et al., 2023). The coding region consists of three functional regions: P1 has four structural proteins (VP1 to VP4), P2 has three non-structural poly-proteins (2A to 2C), and P3 has four non-structural poly-proteins (3A to 3D) (Kemmer & Miskovsky, 2000). Infectious viruses come in two types: naked and non-enveloped HAV virions, which are released into the stool (Yang et al., 2017).

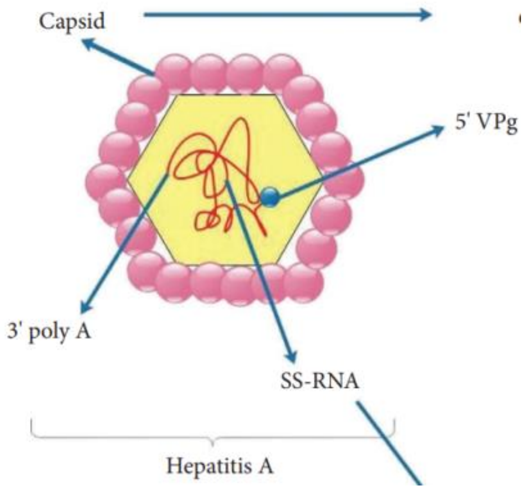

Figure 1. Genome structure of HAV

Source: Gholizadeh et al. (2023).

There are six HAV genotypes based on examining a 168-nucleotide fragment of the VP1-2A region. Only genotypes I, II and III infect humans and genotypes IV to VI cannot infect humans (Smith & Simmonds, 2018). Genotypes I, II, and III are further divided into subtypes A and B (Cella et al., 2018). HAV genotype I is the most common genotype found around the world: HAV genotype IA is prevalent more frequently than IB in South and North America, Europe, Asia and Africa (Ajmera et al., 2011); and HAV genotype IB is found among acute liver failure cases that is predominant in the Middle-East and South Africa (Robertson et al., 1992). HAV genotype II is not as common, and HAV genotype III is common around the world: HAV genotype IIIA circulates in Central Asia, Europe, Madagascar and the USA (Desbois et al., 2010).

7. Clinical Presentation

During the subsequent period, the jaundice disappears and in a majority of cases the disease retreats during 3-6 weeks, and the majority of patients become completely healthy with the physical and psychical activities return (Gluud & Gluud, 2009). Sometimes the patient still suffers from weakness, increased tiredness, arthralgia or dyspeptic disturbances for several months after the recovery from the disease due to posthepatitis syndrome. HAV never progresses into chronicity, but it can cause debilitating symptoms and acute liver failure, which is associated with high mortality (Squires et al., 2006).

There is no evidence of the disease transition to chronic hepatitis and is rarely fatal, and within six months the infected patient is cured completely without causing any longstanding chronic hepatitis (Little et al., 2018). Fulminant hepatitis A is rare but often results in death that occurs primarily in older individuals and in persons with underlying chronic liver disease (CLD) (Wagstaff et al., 1996). In this situation the patient occasionally requires emergency liver transplantation (Yeung & Roberts, 2010).

It is a common disease with serologic evidence of infection by an enterovirus of the Picornaviridae family that causes acute hepatitis (Dentinger et al., 2001). It is typically a self-limiting disease and usually causes mild illness characterized by sudden onset of non-specific symptoms. In addition to the liver, HAV afflicts also other vital organs, such as heart, gastrointestinal tract, pancreas, and spleen (Koff, 1998).

8. Risk Site of HAV Infection

Anyone can be infected by HAV. However, higher risk of HAV infection are injection and non-injection illegal drug users, homeless people, people travel or live in HAV infected areas, persons who has sexual contact with HAV patient, persons with clotting factor disorders, men who have sexual encounters with other men, household members or caregivers of a person infected with HAV, people who may be exposed in a research laboratory setting and those with chronic liver disease, and people who is contacted with an infected person (Sfetcu et al., 2011; Gozlan et al., 2017). Persons who engage in anal pleasuring activities are at increased risk. Health-care personnel do not have an increased prevalence of HAV infections, and nosocomial HAV transmission is rare (WHO, 2016).

9. Transmission of HAV

The source of infection resides in contaminated food and the transmission takes place by the oral pathway through the “fecal-oral” system. When an individual eats or drinks food or water contaminated with HAV may be infected with this virus (Heymann, 2008). Transmission of HAV occurs almost exclusively through the contact of an infected person, traveling to an endemic region, and ingestion of contaminated food and water (enterically). It can spread through the sexual contact or from sharing needles with the infected person (Lemon et al., 2017). The risk of transmission of HAV from pregnant women to newborns seems to be low. If a person has direct contact with an infected person who has poor personal hygiene may be infected with HAV. Sharing of forks, spoons, knives, and other utensils that have virus on them can spread the HAV. The disease is not spread by kissing, sneezing or saliva (WHO, 2012).

Eating food or drinking water, such as fruits, vegetables, salad vegetables, ice, water, certain shellfish (e.g., mussels, oysters and clams), etc. that have been contaminated by feces and contain the virus can spread the HAV. It is spread world-wide and occurs in epidemies predominantly among children and young people who are often asymptomatic (about 70% of kids under six), but accurate figures are lacking. It affects more often organized collectives, such as kindergartens, schools, military units, etc. Breastfeeding is not a mode of transmission (WHO, 2019).

Casual contact, such as in the usual workplace or school setting among people cannot spread the virus (WHO, 2013). If an individual is infected with HAV s/he may not infected further, since it causes lifetime immunity after first infection (Martin & Lemon, 2006). Outbreaks have been reported among men who have sex with men (MSM) and illicit drug users. Oral-anal-vaginal sexual contact with an infected person can spread HAV (WHO, 2016).

10. Symptoms of HAV

Sometimes an individual infected with HAV may have no symptoms or have very mild symptoms. Children younger than six years often have few or no symptoms, but they can still spread the infection. Infants and young children tend to have very mild symptoms than the adults (Wasley et al., 2006). Jaundice may occur in 70–80% of those infected as adults. There is no chronic persistent state and chronic liver damage does not occur. Symptoms of this disease usually appear within 3-4 weeks after swallowing the HAV (Linder & Malani, 2017). Some individuals may infect as quickly as 14 days. Sometimes the patients take as long as two months to be infected (Ciocca, 2000).

Some symptoms of it are fatigue, itching, poor appetite, loss of appetite, low-grade fever, dark urine, nausea, vomiting, anorexia, malaise, diarrhea, headache, febrility, pale or clay-colored stools, and jaundice (yellowing of eyes and skin) (Heymann, 2008). During HAV infection the aspartate aminotransferase (AST) serum level increases and reaches its maximal values. Urine contains serum bilirubin and urobilinogen, but does not increase significantly. The liver is moderately enlarged (Murphy et al., 2013).

11. Diagnosis of HAV

In the laboratory, clinical specimens, such as blood, feces, bile, liver biopsy, and total and direct bilirubin are utilized to detect HAV (Kozak et al., 2022). Detection of HAV is dependent on cell infection assays or molecular techniques for the presence of RNA or DNA (Gerardi & Zimmerman, 2005). Measurement of liver enzyme levels, such as alanine transaminase (ALT), aspartate aminotransferase (AST), alkaline phosphatase (ALP), gamma-glutamyl transpeptidase (GGTP), and serum bilirubin (Koff, 1998); use of molecular virology methods, such as polymerase chain reaction (PCR) and nucleic acid hybridization assays to identify of antigens; specific immunoglobulin M (IgM) antibodies to HAV (anti-HAV) and immunoglobulin G (IgG) antibodies are typically found in the earliest stage of disease by the use of enzyme-linked immunosorbent assay (Nainan et al., 2006).

In HAV infection the alanine transaminase (ALT) level is typically higher than the aspartate transaminase (AST) level, and the range for both is usually between 500 and 5,000 units per litre (Ribeiro et al., 2019). The IgM value ≥ 1 indicates a HAV infection positive result, and a value IgM ≤ 1 indicates a negative result. On the other hand, the IgG value ≥ 120 mIU/ml is considered to be positive HAV infection, and IgG value ≤ 120 mIU/ml indicates negative HAV infection (Pe´rez et al., 2003).

12. Treatment of HAV

No specific medication or antibiotic is available to treat a HAV patient. Treatment of the HAV is palliative and supportive care. Plenty of bed rest, eating healthy and well-balanced foods, drinking plenty of fluids, balanced nutrition, and avoid of drinking any alcohol, acetaminophen and other illegal drugs, may be prescribed especially during the acute phase (WHO, 2013).

Immunoglobulin M (IgM; where M for “macro”) is the largest of several isotypes of antibodies that are produced by vertebrates. It is the first antibody to appear in the response to initial exposure to an antigen (Capolunghi et al., 2013). On the other hand, immunoglobulin G (IgG; where G for “gamma”) is a type of antibody that represents about 75% of serum antibodies in human. It is the most common type of antibody found in blood circulation that is created and released by plasma B cells. Antibodies against the HAV belong to the IgM class, in later period to that of IgG (Cobb, 2019). These can prevent hepatitis A illness if they are given by injection within two weeks of exposure to the HAV (Winokur & Stapleton, 1992).

If a patient has chronic liver disease or a weakened immune system or is a carrier of the viruses and has impaired liver function, then dose modification and supportive care is necessary. About 30% of symptomatic patients require hospitalization for dehydration, severe prostration, coagulopathy, encephalopathy, or other evidence of hepatic decompensation (Brundage & Fitzpatrick, 2006).

13. Prevention of HAV

Prevention strategy of HAV is not costly and difficult. Vaccination of vulnerable populations and children is the most important prevention practice. Postexposure prophylaxis should be offered to all unvaccinated persons who are in higher risk of HAV infection (Fiore, 2004). Physicians should instruct patients about thorough hand washing after defecation and diaper changing, and sanitary disposal of wastes. Ensuring careful food-handling practices, particularly of produce and shellfish, are public health focuses. Gown and gloves should be worn prior to disinfecting and cleaning affected areas (Halliday et al., 1991).

A person must wash hands carefully and thoroughly with soap and warm running water after using the toilet or changing diapers (Chen et al., 2010). S/he must do same process before preparing food and beverages, and before eating. An individual must drink pure water and use bottled water when s/he travels contaminated area (Atkinson, 2005). Everybody should take HAV vaccine to prevent the disease. Undercooked food should avoid and should not wash or prepare food using contaminated water. Raw or steamed shellfish should be avoided (Craig & Schaffner, 2004).

14. HAV Vaccine

The HAV vaccine is very safe and effective. It is made through the killing (inactivated) HAV by formaldehyde (Keeffe, 2006). Vaccine helps the immune system to recognize and fight bacteria and viruses that cause diseases. The HAV vaccine is introduced in 1995 in the USA by American microbiologist Maurice Ralph Hilleman (1919-2005) and his team that saves millions of lives every year (CDC, 2018). It is used to prevent infection caused by HAV. It is recommended for all children ages 12 to 23 months (Fiore et al., 2008).

At present four monovalent HAV vaccines are currently available in two classes of single-antigen inactivated viruses. These provide active immunization against HAV: i) three vaccines: Havrix® (GlaxoSmithKline), Avaxim® (Sanofi), and VAQTA® (Merck Sharp & Dohme (UK) Limited) are adsorbed onto an aluminium hydroxide adjuvant; and ii) the fourth Epaxal® (Berna Biotech Ltd, Bern, Switzerland), contains formalin-inactivated hepatitis A particles (Ambrosch et al., 2004). Epaxal can be injected intramuscularly, which is well tolerated and induces a rapid HAV neutralizing antibody response resulting in seroprotection (Loutan et al., 1994). These vaccines can be used interchangeably (Beck et al., 2004). Combined vaccine Twinrix® (GlaxoSmithKline) contains purified inactivated HAV adsorbed onto aluminium hydroxide that can be used for the protection against both HAV and HBV (Joines et al., 2001; Stoffel et al., 2003). Another combined vaccine Ambirix® (GlaxoSmithKline) contains purified recombinant HBV surface antigen adsorbed onto aluminium phosphate that also can be used for the protection against both HAV and HBV (Jarvis & Figgitt, 2003; Beran, 2007).

To produce each vaccine, cell culture adapted virus is propagated in human fibroblasts, purified from cell lysates, inactivated with formalin, and adsorbed to an aluminum hydroxide adjuvant. A single dose of HAV vaccine provides protection for at least a year. A second dose is recommended to provide long lasting protection. Two doses of HAV vaccine at least six months apart are needed to be fully protected (Ott et al., 2012).

Most people have no side-effects of the vaccine, except mild soreness at the site of the injection. However, some less common side-effects (among about 5% people) are soreness at the site of injection, loss of appetite, tiredness, low-grade fever, drowsiness, dizziness, headache, etc. side effects are usually mild and only last a short-time (Bovier et al., 2002). Acetaminophen may be given for fever and soreness, but aspirin must not be given. If more severe life-threatening allergies or side-effects are seen, such as anaphylaxis (e.g., rashes or hives, swelling of the face and throat, difficulty breathing, a fast heartbeat, etc.), the vaccination should be discontinued (Czeschinski et al., 2000).

Vaccines are sensitive to some extent to heat and cold, and should be stored in the original packaging at +2°C to +8°C, and should be protected from light. Heat speeds up the decline in potency of HAV and reduces the shelf life. Freezing causes increased reactogenicity and loss of potency of HAV (WHO, 2018).

15. Conclusions

From this study we have observed that hepatitis A is a viral infection of the liver that may cause a short-term sickness of the liver and usually does not cause complex liver problem. The disease is not last for a long-time. The clinical course of HAV is age-dependent and the infection tends to progress from infant in form to more severe forms in adults. The HAV usually spreads through the direct contact with an infected person. It is also transmitted through fecal contamination of food and water. HAV infection can result in a financial and social burden to students, teacher, workers, and other service holders. Recently, improvements in socioeconomic condition, personal hygiene, sanitation, and vaccination HAV infection rates have declined in both developed and low-income countries. Two vaccines of HAV are approved and available, and two doses at least six months apart remain active for life-long immunization.

References

Aggarwal, R., Goel, A., (2015). Hepatitis A: Epidemiology in Resource-Poor Countries. *Current Opinion in Infectious Diseases*, *28*(5), 488-496.

Ahmad, T. et al., (2021). Trends in Hepatitis A Research Indexed in the Web of Science: A Bibliometric Analysis over the Period from 1985 to 2019. *Human Vaccines & Immunotherapeutics*, *17*(9), 3221-3229.

Ajmera, V. et al., (2011). Acute Liver Failure Study Group. What Factors Determine the Severity of Hepatitis A-Related Acute Liver Failure. *Journal of Viral Hepatitis*, *18*(7), e167-e174.

Ambrosch, F. et al., (2004). Rapid Antibody Response after Vaccination with a Virosomal Hepatitis A Vaccine. *Infection*, *32*(3), 149-152.

Atkinson, W., (2005). *Hepatitis A. Epidemiology and Prevention of Vaccine-Preventable Diseases* (8th Ed.). Atlanta, Ga.: Centers for Disease Control and Prevention.

Beck, B. R. et al., (2004). Immunogenicity of Booster Vaccination with a Virosomal Hepatitis A Vaccine after Primary Immunisation with an Aluminium-Adsorbed Hepatitis A Vaccine. *Journal of Travel Medicine*, *11*(4), 201-207.

Beran, J., (2007). Bivalent Inactivated Hepatitis A and Recombinant Hepatitis B Vaccine. *Expert Review of Vaccines*, *6*(6), 891-902.

Bovier, P. A. et al., (2002). Longterm Immunogenicity of an Inactivated Virosome Hepatitis A Vaccine. *Journal of Medical Virology*, *68*(4), 489-493.

Brundage, S. C., Fitzpatrick, E. N., (2006). Hepatitis A. *American Family Physician*, *73*(12), 2162-2168.

Capolunghi, F. et al., (2013). Why Do We Need IgM Memory B Cells? *Immunology Letters*, *152*(2), 114-120.

Cella, E. et al., (2018). The Genetic Diversity of Hepatitis A Genotype I in Bulgaria. *Medicine*, *97*(3), Article ID e9632.

Centers for Disease Control and Prevention (CDC), (2018). Hepatitis A Questions and Answers for Health Professionals. https://www.cdc.gov/Hepatitis/hav/havfaq.htm#general.

Chen, J. Y. et al., (2010). Changing Prevalence of Anti-Hepatitis A Virus in Adolescents in a Rural Township in Taiwan. *Chang Gung Medical Journal*, *33*(3), 321-326.

Ciocca, M., (2000). Clinical Course and Consequences of Hepatitis A Infection. *Vaccine*, *18*(Supppl 1), S71-S74.

Cobb, B. A., (2019). The History of IgG Glycosylation and Where We Are Now. *Glycobiology*, *30*(4), 202-213.

Craig, A. S., Schaffner, W., (2004). Prevention of Hepatitis A with the Hepatitis A Vaccine. *New England Journal* *of Medicine*, *350*(5), 476-481.

Czeschinski, P. A. et al., (2000). Hepatitis A and Hepatitis B Vaccinations: Immunogenicity of Combined Vaccine and of Simultaneously or Separately Applied Single Vaccines. *Vaccine*, *18*(11-12), 1074-1080.

Dentinger, C. M. et al., (2001). A Prevalence Study of Hepatitis A Virus Infection in a Migrant Community: Is Hepatitis A Vaccine Indicated? *Journal of Pediatrics*, *138*(5), 705-709.

Desbois, D. et al., (2010). Epidemiology and Genetic Characterization of Hepatitis A Virus Genotype IIA. *Journal of Clinical Microbiology*, *48*(9), 3306-3315.

Enkirch, T. et al., (2019). Improving Preparedness to Respond to Cross-Border Hepatitis A Outbreaks in the European Union/European Economic Area: Towards Comparable Sequencing of Hepatitis A Virus. *Euro Surveillance*, *24*(28), 1800397.

Fiore, A. E., (2004). Hepatitis A Transmitted by Food. *Clinical Infectious Diseases*, *38*(5), 705-715.

Fiore, A. E. et al., (2008). Hepatitis A Vaccines. In: Plotkin, S., Orenstein, W., Offit, P., (Eds.). *Vaccines*, 177-196, 5th Ed., China, Saunders Elsevier Inc.

Food and Drug Administration (FDA), (2012). Foodborne Pathogenic Microorganisms and Natural Toxins (2nd Ed.). *Hepatitis A Virus*, 173-178. Bad Bug Book.

Franco, E. et al., (2012). Hepatitis A: Epidemiology and Prevention in Developing Countries. *World Journal of Hepatology*, *4*(3), 68-73.

Gerardi, M. H., Zimmerman, M. C., (2005). *Wastewater Pathogens*. Hoboken, NJ: Wiley Interscience.

Gholizadeh, O. et al., (2023). Hepatitis A: Viral Structure, Classification, Life Cycle, Clinical Symptoms, Diagnosis Error, and Vaccination. *Canadian Journal of Infectious Diseases and Medical Microbiology*, *2023*(5), Article ID: 4263309.

Gluud, L. L., Gluud, C., (2009). Meta-analyses on Viral Hepatitis. *Infectious Disease Clinics of North America*, *23*(2), 315-330.

Gow, P. J., Mutimer, D., (2001). Treatment of Chronic Hepatitis. *BMJ*, *323*(7322), 1164-1167.

Gozlan, Y. et al., (2017). Ongoing Hepatitis A among Men Who Have Sex with Men (MSM) Linked to Outbreaks in Europe in Tel Aviv Area, Israel, December 2016-June 2017. *Euro Surveillance*, *22*(29), 30575.

Hallberg, L., (2006). The “Core-Category” of Grounded Theory: Making Constant Comparisons. *International Journal of Qualitative Studies on Health and Well-being*, *1*(3), 141-148.

Halliday, M. L. et al., (1991). An Epidemic of Hepatitis A Attributable to the Ingestion of Raw Clams in Shanghai, China. *Journal of the Infectious Diseases*, *164*(5), 852-859.

Heymann, D. L., (2008). *Viral Hepatitis A. In: Control of Communicable Diseases Manual*, 19th Ed., 278-284. American Public Health Association, Washington.

Jacobsen, K. H., Wiersma, S. T., (2010). Hepatitis A Virus Seroprevalence by Age and World Region, 1990 and 2005. *Vaccine*, *28*(40), 6653-6657.

James, T. L. et al., (2009). Response to Hepatitis A Epidemic: Emergency Department Collaboration with Public Health Commission. *Journal of Emergency Medicine*, *36*(4), 412-416.

Jarvis, B., Figgitt, D. P., (2003). Combined Two-Dose Hepatitis A and B Vaccine (AmBirix). *Drugs*, *63*(2), 207-213.

Joines, R. W. et al., (2001). A Prospective, Randomized, Comparative US Trial of a Combination Hepatitis A and B Vaccine (Twinrix®) with Corresponding Monovalent Vaccines (Havrix® and Engerix-B®) in Adults. *Vaccine*, *19*(32), 4710-4719.

Keeffe, E. B., (2006). Hepatitis A and B Superimposed on Chronic Liver Disease: Vaccine-Preventable Diseases. *Transactions of the American Clinical and Climatological Association*, *117*, 227-237.

Keeffe, E. B. et al., (1998). Safety and Immunogenicity of Hepatitis A Vaccine in Patients with Chronic Liver Disease. *Hepatology*, *27*(3), 881-886.

Kemmer, N. M., Miskovsky, E. P., (2000). Hepatitis A. *Infectious Disease Clinics of North America*, *14*(3), 605-615.

Koff, R. S., (1998). Hepatitis A. *Lancet*, *351*(9116), 1643-1649.

Kothari, C. R., (2008). *Research Methodology: Methods and Techniques* (2nd Ed.). New Delhi: New Age International (P) Ltd.

Kozak, R. A. et al., (2022). Development and Evaluation of a Molecular Hepatitis A Virus Assay for Serum and Stool Specimens. *Viruses*, *14*(1), 159.

Kulsuptrakul, J. et al., (2021). A Genome-Wide CRISPR Screen Identifies UFMylation and TRAMP-like Complexes as Host Factors Required for Hepatitis A Virus Infection. *Cell Reports*, *34*(11), Article ID 108859.

Lednar, W. M. et al., (1985). Frequency of Illness Associated with Epidemic Hepatitis A Virus Infections in Adults. *American Journal of Epidemiology*, *122*(2), 226-233.

Legesse, B., (2014). *Research Methods in Agribusiness and Value Chains*. School of Agricultural Economics and Agribusiness, Haramaya University.

Lemon, S. M. et al., (2017). Type A Viral Hepatitis: A Summary and Update on the Molecular Virology, Epidemiology, Pathogenesis and Prevention. *Journal of Hepatology*, *S0168-8278*(17), 32278.

Linder, K. A., Malani, P. N., (2017). Hepatitis A. *JAMA*, *318*(23), 2393.

Little, J. W. et al., (2018). *Dental Management of the Medically Compromised Patient* (9th Ed.) St. Louis: Missouri.

Loutan, L. et al., (1994). Inactivated Virosome Hepatitis A Vaccine. *Lancet*, *343*(8893), 322-324.

Martin, A., Lemon, S. M., (2006). Hepatitis A Virus: From Discovery to Vaccines. *Hepatology*, *43*(2 Suppl 1), S164-S172.

Mohajan, H. K., (2017). Two Criteria for Good Measurements in Research: Validity and Reliability. *Annals of Spiru Haret University Economic Series*, *17*(3), 58-82.

Mohajan, H. K., (2018). Aspects of Mathematical Economics, Social Choice and Game Theory. PhD Dissertation, Jamal Nazrul Islam Research Centre for Mathematical and Physical Sciences (JNIRCMPS), University of Chittagong, Chittagong, Bangladesh.

Mohajan, H. K., (2020). Quantitative Research: A Successful Investigation in Natural and Social Sciences. *Journal of Economic Development, Environment and People*, *9*(4), 50-79.

Mohajan, H. K., (2024a). Alcoholic Liver Disease: Diagnosis and Treatment Strategies. Unpublished Manuscript.

Mohajan, H. K., (2024b). Alcoholic Hepatitis: Diagnosis and Management Procedures. Unpublished Manuscript.

Mohajan, H. K., (2024c). Anatomy of Human Liver: A Theoretical Study. Unpublished Manuscript.

Mohajan, H. K., (2024d). Liver Diseases: Epidemiology, Prevention, and Management Strategy. Unpublished Manuscript.

Mohajan, H. K., (2024e). A Study on Functions of Liver to Sustain a Healthy Liver. Unpublished Manuscript.

Murphy, T. V. et al., (2013). Hepatitis A Vaccines. In: Plotkin, S. A., Orenstein, W. A., Offit, P. A., (Eds.), *Vaccines*, 6th Ed., 183-204, Philadelphia: Elsevier.

Nainan, O. V. et al., (2006). Diagnosis of Hepatitis A Virus Infection: A Molecular Approach. *Clinical Microbiology Reviews*, *19*(1), 63-79.

Ott, J. J. et al., (2012). Long-term Protective Effects of Hepatitis A Vaccines: A Systematic Review. *Vaccine*, *31*(1), 3-11.

Pandey, P., Pandey, M. M., (2015). *Research Methodology: Tools and Techniques*. Bridge Center, Romania, European Union.

Pe´rez, O. M. et al., (2003). Efficacy of Virosome Hepatitis A Vaccine in Young Children in Nicaragua: Randomized Placebo-Controlled Trial. *Journal of Infectious Diseases*, *188*(5), 671-677.

Persson, S. et al., (2021). A New Assay for Quantitative Detection of Hepatitis A Virus. *Journal of Virological Methods*, *288*(2021), 114010.

Polit, D. F., Hungler, B. P., (2013). *Essentials of Nursing Research: Methods, Appraisal, and Utilization* (8th Ed.). Philadelphia: Wolters Kluwer/Lippincott Williams and Wilkins.

Ribeiro, C. R., et al., (2019). Accuracy of Rapid Test for Diagnosis of Hepatitis A with Different Infection Rate Settings and with Predictive Modeling. *Future Microbiology*, *14*(3), 247-258.

Robertson, B. H. et al., (1992). Genetic Relatedness of Hepatitis A Virus Strains Recovered from Different Geographical Regions. *Journal of General Virology*, *73*(Pt 6), 1365-1377.

Savicka, O., (2022). Molecular Epidemiology of Hepatitis A Outbreaks and Sporadic Cases, Latvia, 2017 to

2019. *Euro Surveillance*, *27*(11), Article ID 2100415.

Sfetcu, O. et al., (2011). Hepatitis A Outbreak Predominantly Affecting Men Who Have Sex with Men in Northern Ireland, October 2008 to July 2009. *Euro Surveillance*, *16*(9), Article ID 19808.

Smith, D. B., Simmonds, P., (2018). Classification and Genomic Diversity of Enterically Transmitted Hepatitis Viruses. *Cold Spring Harbor Perspectives in Medicine*, *8*(9), Article ID a031880.

Sood, V. et al., (2019). Hepatitis A Virus-related Pediatric Liver Disease Burden and Its Significance in the Indian Subcontinent. *Indian Pediatrics*, *56*(9), 741-744.

Squires, R. H. Jr. et al., (2006). Acute liver Failure in Children: The First 348 Patients in the Pediatric Acute Liver Failure Study Group. *Journal of Pediatrics*, *148*(6), 652-658.

Stoffel, M. et al., (2003). Immunogenicity of Twinrix™ in Older Adults: A Critical Analysis. *Expert Review of Vaccines*, *2*(1), 9-14.

Venes, D., Taber, C. W., (2013). *Taber's Cyclopedic Medical Dictionary* (22nd Ed.). Philadelphia: F.A. Davis.

Wagstaff, A. J. et al., (1996). Inactivated Hepatitis A Vaccine (HM175 Strain): A Preliminary Review of Its Immunogenicity, Protective Potential and Tolerability in At-Risk Patients. *Clinical Immunotherapy*, *6*(Suppl 1), S68-S88.

Wasley, A. et al., (2006). Hepatitis A in the Era of Vaccination. *Epidemiologic Reviews*, *28*(1), 101-111.

Wasley, A. et al., (2010). Hepatitis A Virus. In Mandell, G. L., Bennett, J. E., & Dolin, R. (Eds.). *Principles and Practice of Infectious Diseases* (7th Ed.), Elsevier, Philadelphia.

WHO, (2012). Position Paper on Hepatitis A Vaccines–June 2012. World Health Organization (WHO). *Weekly Epidemiological Record*, *87*(12), 261-276. http://www.who.int/wer/2012/wer8728_29.pdf?ua=1.

WHO, (2013). Hepatitis A. Geneva: World Health Organization. http://www.who.int/mediacentre/factsheets/fs328/en/index.html.

WHO, (2016). Technical Considerations and Case Definitions to Improve Surveillance for Viral Hepatitis. Geneva: World Health Organization. World Health Organization (WHO). http://apps.who.int/iris/bitstream/10665/204501/1/9789241549547_eng.pdf.

WHO, (2018). Vaccine-Preventable Diseases: Monitoring System. Global Summary. http://apps.who.int/immunization_monitoring/globalsummary/countries?

WHO, (2019). WHO Immunological Basis for Immunization Series: Module 18: Hepatitis A. Geneva: World Health Organization.

Winokur, P. L, Stapleton, J. T., (1992). Immunoglobulin Prophylaxis for Hepatitis A. *Clinical Infectious Diseases*, *14*(2), 580-586.

Yang, X. et al., (2017). Structures and Corresponding Functions of Five Types of Picornaviral 2A Proteins. *Frontiers in Microbiology*, *8*, 1373.

Yeung, L. T., Roberts, E. A., (2010). Current Issues in the Management of Paediatric Viral Hepatitis. *Liver International*, *30*(1), 5-18.

Zeng, D. Y. et al., (2021). Global Burden of Acute Viral Hepatitis and Its Association with Socioeconomic Development Status, 1990-2019. *Journal of Hepatology*, *75*(3), 547-556.

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Research Progress in Lithium Recycling: A Mini Review

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Abstract

The execution of the dual carbon strategy has expedited the swift advancement of the new energy sector, resulting in a substantial rise in the demand for lithium resources. The process of lithium recycling can mitigate the environmental challenges associated with lithium extraction, thereby underscoring the growing importance of lithium recycling. This paper focuses on the essential technologies utilized for the recovery of lithium and other metals from diverse categories of waste lithium-ion batteries. These technologies include pyrometallurgy, hydrometallurgy, and bio-metallurgy. Additionally, the paper delineates the various stages involved in the recycling process. This paper conducts a comparative analysis of various technologies used for lithium recovery, examining their respective processes, advantages and disadvantages, efficiency in lithium recovery, associated costs, environmental implications, and degree of commercialization. While there is a growing concern regarding the advancement of various lithium recycling technologies, the current efficiency of lithium recycling remains significantly constrained. It is anticipated that this paper will further stimulate interest in the field of lithium recycling.

Keywords: dual carbon strategy, lithium recycling, bio-metallurgy, environmental impact, commercialization

1. Introduction

Lithium, a lightweight metal commonly known as a green energy metal and referred to as “white oil”, is extensively employed across multiple sectors, including energy storage, the chemical industry, medicine, metallurgy, and electronics. At the regional level, lithium resources are predominantly located in South American nations, specifically Bolivia and Chile, in addition to Argentina, China, and the United States, as illustrated in Figure 1b. Lithium extraction predominantly occurs from Salt Lake brines and mineral ores, with a total of 72.3% of the identified resource reserves located in Salt Lake brines, and 20.3% situated in ores. Notably, approximately 40% of the world’s lithium is derived from ores, whereas production from Salt Lake brine surpasses 60% (Bae, H. & Kim, Y., 2021). Lithium demonstrates considerable reactivity, a notable electrochemical potential, and a high energy density, making it an optimal material for use in battery applications. As illustrated in Figure 1a, approximately 65% of lithium is utilized within the battery industry, 18% is dedicated to the manufacturing of glass and ceramics, while the remaining 17% is primarily assigned to various other applications, including polymers and lubricants (Tadesse, B., Makuei, F., Albijanic, B. & Dyer, L., 2019). In recent years, there has been a significant increase in the demand for electric vehicles, driven by heightened public awareness regarding environmental conservation, advancements in lithium battery technology, and supportive government initiatives. As illustrated in Figure 1c, the timeframe spanning from 2021 to 2024 is characterized by notably substantial growth in electric vehicle sales within China, in contrast to the more moderate growth observed in other regions (IEA, 2024). It is projected that in 2024, sales of electric vehicles may attain 17 million units, accounting for roughly one-fifth of the total automobile sales (IEA, 2024). Nonetheless, the efficacy of lithium batteries declines with the passage of time, suggesting that the volume of decommissioned lithium batteries is expected to rise substantially in the future, thereby presenting challenges for their management. While used batteries may pose challenges in waste management, they simultaneously provide manufacturers with the opportunity to obtain essential materials from a secondary source.

The extensive extraction of lithium often results in numerous adverse effects on the environment. In specific lithium mining areas, including the Atacama Salt Flat in Chile, the prevailing method of lithium extraction is significantly water-intensive, requiring the evaporation of 500,000 gallons of water for every ton of lithium produced. It is estimated that mining operations consume approximately 65% of the region's water resources, which has a detrimental effect on local farmers (Katwala, A., 2018). The International Energy Agency (IEA) forecasts that by the year 2040, the recovery of copper, lithium, nickel, and cobalt from batteries may fulfill 10% of the demand for these minerals. This advancement has the potential to significantly reduce dependence on mineral extraction and contribute to the alleviation of the environmental challenges associated with mining activities (International Energy Agency (IEA), 2025). Simultaneously, the improper disposal or inadequate management of lithium batteries can present significant risks to the health of animals, plants, and humans. This is primarily due to the potential leaching, decomposition, and degradation of the hazardous substances contained within these batteries (Energy & Environmental Science, 2021). Consequently, from the standpoint of environmental conservation, the appropriate recycling of lithium can alleviate adverse effects on the ecosystem. From an economic perspective, profitability is generally achieved through the recycling of high-value components, such as copper derived from cobalt, lithium iron phosphate batteries, and lithium manganese oxide batteries, which represent substantial revenue sources (Lander, L. et al., 2021). Despite the existing limitations in recycling efficiency and the high costs associated with the recycling process, there remains substantial potential for advancements in relevant technologies. Nonetheless, lithium recycling presents notable economic benefits. Recent studies suggest that the electrochemical extraction of lithium can reduce costs by 35.6% in comparison to conventional extraction methods, while simultaneously reducing carbon dioxide emissions by 75.3% (Bae, H. & Kim, Y., 2021; Zhang, H. et al., 2024). Consequently, advancements in technology are crucial for the successful implementation of lithium recycling processes.

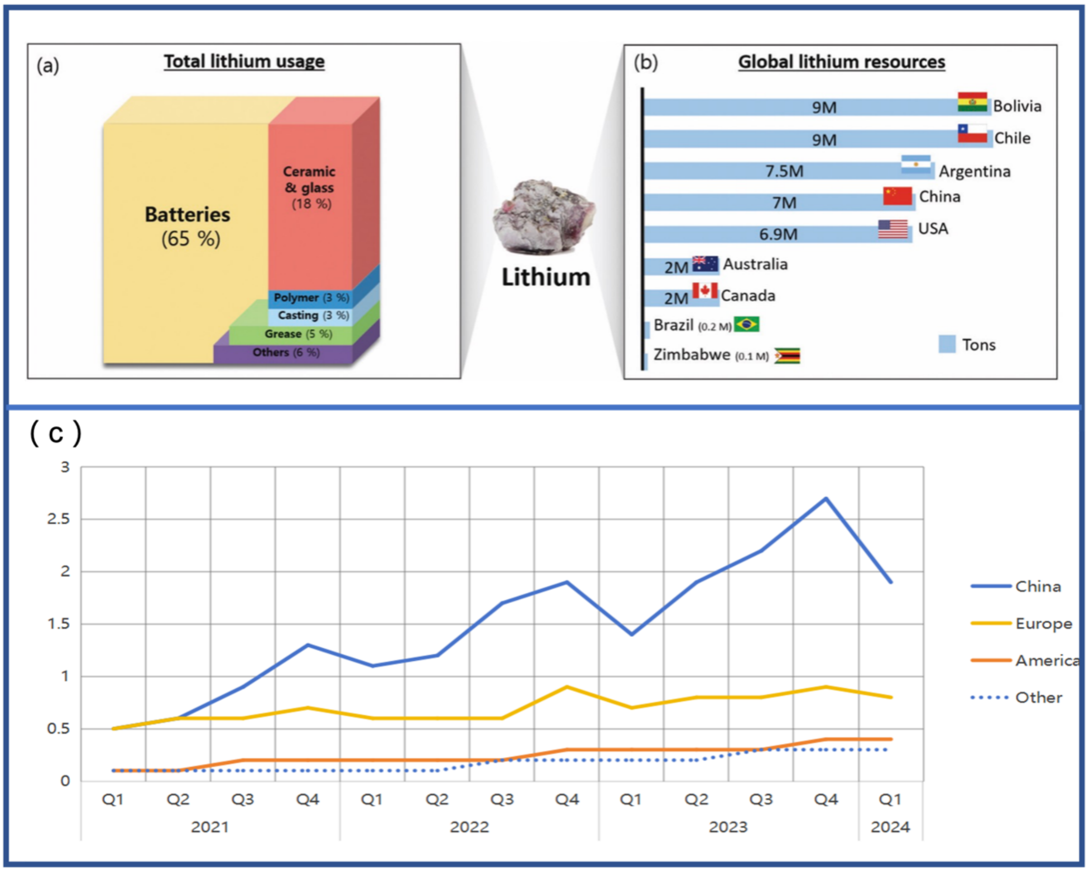

Figure 1. (a) Distribution of total lithium usage in 2019 (Tadesse, B. et al., 2019); (b) distribution of global lithium (Bae, H. & Kim, Y. 2021); (c) Quarterly electric car sales by region, 2021-2024 (IEA, 2024)

2. Primary Sources of Lithium Material Recycling

It is projected that a considerable quantity of lithium-ion batteries will reach the end of their operational life in

2025. These decommissioned batteries generally contain valuable metals such as lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), and copper (Cu) (Wojciech Mrozik et al., 2021). The recycling of these metals not only fosters sustainable development but also mitigates the environmental pollution associated with the disposal of lithium batteries. In addition to discarded batteries, lithium materials can also be reclaimed from the byproducts produced during the extraction of lithium ores and the manufacturing of lithium salts. These byproducts may contain lithium compounds that have not been completely recovered. By employing suitable processing methods, lithium can be effectively extracted from these materials.

2.1 Extraction of Lithium from Waste Batteries

The recycling of lithium materials predominantly stems from lithium batteries, especially lithium-ion batteries, which are extensively employed in rechargeable batteries. Lithium-ion batteries are primarily composed of positive electrode materials, negative electrode materials, electrolytes, current collectors, and sheathing materials. Notably, the high-value elements present in the positive electrode materials, along with the aluminum and copper utilized in the current collectors, hold considerable value for recycling purposes. As illustrated in Figure 2a, lithium-ion batteries can be categorized into various types, including lithium cobalt oxide (LCO) batteries, nickel cobalt manganese oxide (NMC) batteries, nickel cobalt aluminum oxide (NCA) batteries, lithium iron phosphate (LFP) batteries, and lithium manganese oxide (LMO) batteries. This classification is based on their chemical composition and the proportions of the materials that comprise them (Duan, X. et al., 2022). As illustrated in Figure 2b, fluctuations in chemical composition result in notable disparities in the recycling value of these batteries, with the presence of cobalt and nickel frequently being a pivotal factor. For example, the NMC111 battery, which possesses the highest recycling value, also contains the greatest concentration of cobalt, yielding approximately USD 42 in revenue for each kilowatt-hour of this battery type that is recycled. Conversely, lithium iron phosphate (LFP) batteries pose more significant challenges for commercial recycling due to the lack of high-value metals (Toro, L. et al., 2023).

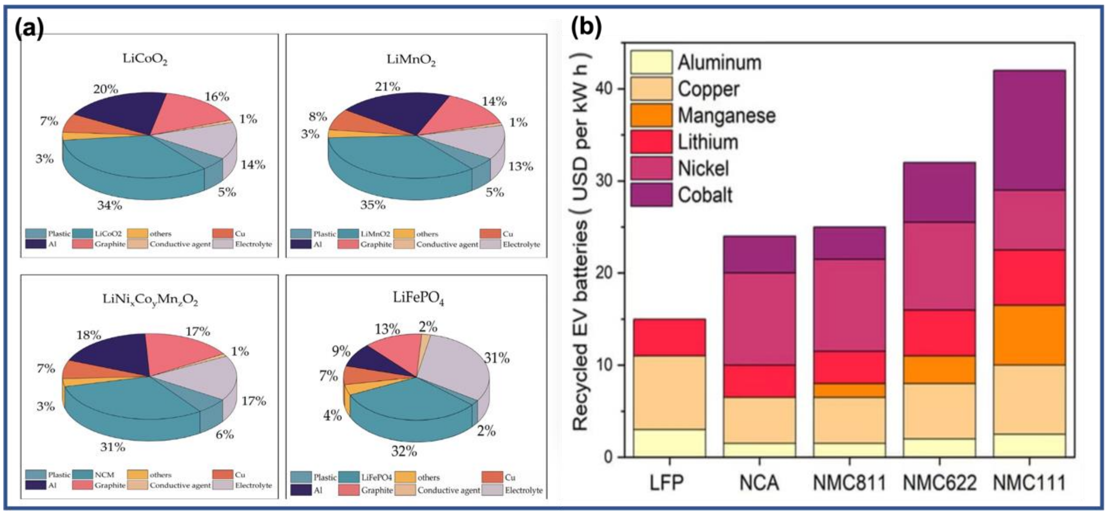

Figure 2. (a) Composition of different types of lithium-iron batteries (Duan, X. et al., 2022); (b) Recycling value of different types of EV batteries (Toro, L. et al., 2023)

2.2 Extraction of Lithium from Lithium Slags

Lithium slag refers to the byproduct produced during the smelting and manufacturing processes of lithium ore, which is formed at elevated temperatures. The primary constituents of lithium slag include silicon dioxide, aluminum oxide, and a range of other oxides, as detailed in Table 1. In industrial contexts, the production of one ton of lithium carbonate generally yields between 30 to 40 tons of lithium slags, thereby presenting a considerable challenge in terms of disposal due to the large volumes generated (Zhai M., Zhao J. & Wang D., 2017; Li, J. & Huang, S., 2020). Owing to its hydration activity, recycled lithium slag is frequently employed in the construction materials industry as a cement additive, which is regarded as the most effective means of utilizing lithium slag. Additionally, it is utilized in the formulation of clinker-free concrete and as a binding agent for mine filling materials, among various other applications. In the chemical sector, the silicon and aluminum components of lithium slag are harnessed in the production of molecular sieves, the manufacture of white carbon black, and the firing of ceramic aggregates and glazed tiles, among other purposes (Liu, C. Y. & Lu, J. S., 2023).

Lithium slag may also be utilized as a potential source for the extraction of lithium. Research has shown that lithium carbonate and lithium hydrate can be synthesized using acidified roasting and causticizing reaction techniques. In this procedure, lithium slag is integrated with spodumene, and through the process of acidified roasting, lithium is transformed into lithium sulfate. Following filtration, the resultant leachate undergoes a reaction with carbonate to yield lithium carbonate. This lithium carbonate can subsequently be mixed with lime, resulting in a causticizing reaction that produces lithium hydroxide. The caustic residue generated from this reaction can be reintroduced into the roasting process, thereby substantially improving the recovery rate (Wang, X., Wang, H. & Wang, Q., 2022).

Table 1. Main components of Lithium Slag

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	Loss	–	Sum
47.62	21.56	2.02	0.48	0.12	0.03	10.68	3.05	3.46	0.14	10.84	100

2.3 Alternative Methods for Lithium Recovery

In addition to the extraction of lithium from lithium slag and discarded batteries, other suitable sources include industrial wastewater, lake water and seawater. In the process of lithium extraction from seawater, specific adsorbent materials characterized by high specific surface area have proven effective in adsorbing lithium ions from seawater. Experimental studies have shown that coal ash and slag generated from circulating fluidized bed combustion (CFBC) technology exhibit a significant capacity for the efficient adsorption of lithium ions from seawater. The adsorption efficiencies of lithium utilizing coal ash and slag are recorded at 12.1% and 6.8%, respectively (Kalak, T. & Tachibana, Y., 2021). The waste produced during the lithium extraction process from salt lakes generally contains lithium constituents that have not been completely extracted. For example, during this procedure, a solution may be left behind that contains impurities such as potassium and magnesium. The solution could potentially undergo further treatment to facilitate the additional extraction of lithium.

3. Recycling Process of Lithium Batteries

Lithium-ion batteries represent the principal source for the recycling of lithium materials. The recycling process not only aids in the recovery of lithium but also allows for the extraction of several high-value elements, such as cobalt and nickel, thus yielding significant economic advantages. The recycling process involves multiple steps, which include preprocessing, discharge, pyrometallurgy, and hydrometallurgy, and encompasses a range of methodologies.

3.1 Preprocessing

Preprocessing generally encompasses a series of operations, including discharging, dismantling, crushing, sorting, separating, dissolving, and thermal treatment (Kim, S., 2021). The procedures associated with preprocessing are of paramount importance. The inadequate execution of preprocessing may result in the ignition of lithium batteries during the recycling process. This, in turn, could lead to damage to recycling machinery and present a considerable risk to the environment (Wojciech Mrozik et al., 2021; Hu, L. Q. 2022).

3.1.1 Discharge

Discarded electronic devices will initially be subjected to recycling processes and undergo preliminary disassembly. Prior to the disassembly of the battery, it is imperative to first discharge it. This precautionary measure is implemented to mitigate the risk of fires and explosions, thereby safeguarding the safety of personnel and preserving the integrity of the disassembly equipment. In most cases, the discharge undergoes a thermal pretreatment, as illustrated in Figure 3. Solutions of sodium chloride (NaCl), manganese sulfate ($MnSO_4$), and iron sulfate ($FeSO_4$) are frequently utilized as discharge media. It is essential to recognize that the efficiency of the discharge process and the resultant products are influenced by the specific type of discharge media employed. Among the available media, ferrous sulfate has been demonstrated to exhibit the highest discharge efficiency, with the predominant residues comprising copper and iron. The gases released are comparatively environmentally benign (Yao, L. P. et al, 2020). Furthermore, Na_2S and $MgSO_4$ may also serve as effective discharge media. Studies suggest that the efficiency of discharge is more significantly influenced by the molar concentration of the solution rather than its ionic strength (Torabian, M. M., Jafari, M. & Bazargan, A., 2021).

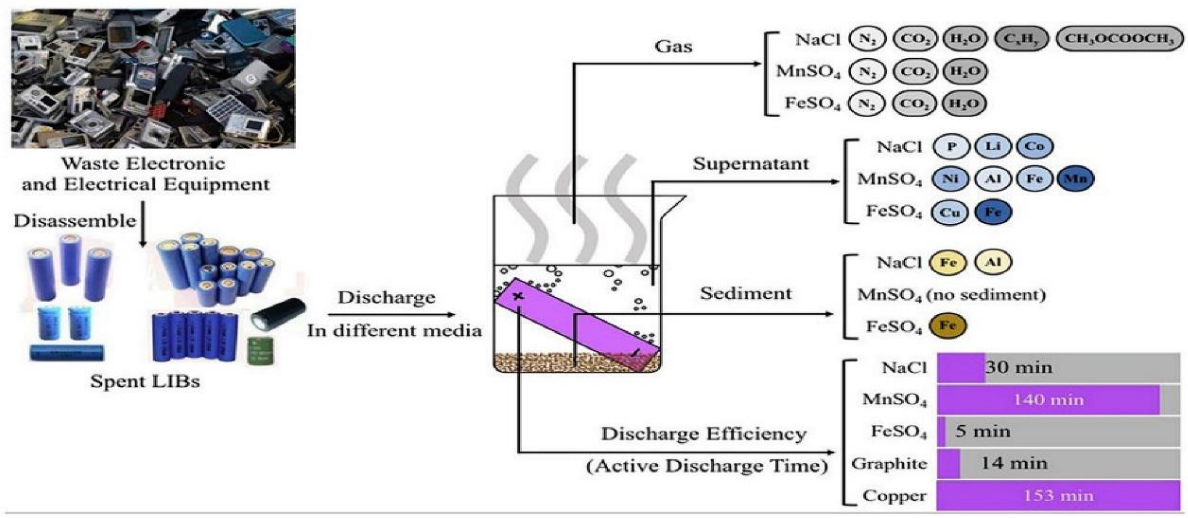

Figure 3. Discharging lithium-iron batteries by different solutions (Yao, L. P. et al, 2020)

3.1.2 Mechanical Processing, Separation, Dissolution, and Thermal Treatment

Following the discharge of a lithium-ion battery, the initial step will involve mechanical processing. Mechanical preprocessing includes various processes, such as crushing, screening, magnetic separation, fine crushing, and classification. Nevertheless, it is important to note that mechanical processing may pose a risk of equipment damage during the stages of magnetic separation and screening. Magnetic separation is an efficient method for isolating metal particles from various materials, including shells, copper foil, and aluminum foil. Subsequent processes, including solvent treatment, calcination, and physical separation, are then employed to obtain copper, aluminum, black matter, and plastics. The black matter is comprised of a combination of cathode and anode active materials, which possess a considerable recycling value (Ekberg, C., Petranikova, M., 2015; Neumann, J. et al., 2022; Zhao, G. J. et al., 2024). The active materials obtained can undergo additional processing to extract valuable metals through the methods of pyrometallurgy, electrolysis, and hydrometallurgy.

3.2 Pyrometallurgy

Pyrometallurgy is a conventional metallurgical technique that entails the extraction of metals and other valuable substances via high-temperature processing. In the field of lithium battery recycling, pyrometallurgy predominantly utilizes high-temperature smelting and roasting methods. This approach is advantageous for its wide applicability and ease of operation, rendering it a favored option for the large-scale processing of lithium batteries (Zhao, G. J. et al., 2024). Nonetheless, pyrometallurgy presents several drawbacks, including elevated energy consumption, considerable gas emissions, low recovery efficiency, and the inability to recover specific metals, leading to significant material losses (Villen-Guzman, M. et al., 2024). The primary challenges associated with pyrometallurgy include high energy consumption, integration with other processes, and the reduction of environmental pollution. In pyrometallurgy, additives such as sulfides and chlorides are utilized to regulate temperature and enhance efficiency. Alternatively, emerging technologies, such as Flash Joule Heating, can be employed to mitigate environmental impact and improve economic benefits. By incorporating it with additional processes, it is feasible to mitigate the constraints associated with pyrometallurgy (Mei, Y. R. et al., 2024). Addressing these challenges has a profound effect on environmental conservation and contributes to the enhancement of economic advantages.

Table 2. Comparing Pyrometallurgy and Hydrometallurgy

Process	Advantages	Disadvantages	Challenges
Pyrometallurgy	• Simple operation • No requirement for pretreatment • High efficiency	• High energy consumption • More waste gasses • Low efficiency of recovery • Li and Mn are not recovered	• Decreasing energy consumption, pollution, emissions and environmental hazards • Combining it with hydrometallurgy
Hydrometa-llurgy	• High recovery rate • High purity product • Low energy consumption • Less waste gas • High efficiency	• More consumption of water and chemical reactants • More wastewater • Long process	• Wastewater treatment • Optimization of the process • Circular hydrometallurgy

The batteries that have been preprocessed are gathered and subsequently subjected to pyrometallurgical roasting. Due to lithium's strong oxytropism, it generally manifests as slag after the roasting procedure. When lithium batteries are exposed to elevated temperatures, the extraction of lithium and cobalt is facilitated through the incorporation of reducing agents and slag modifiers. This procedure yields a cobalt alloy and slag composed of CoO and C_3O_4, in addition to Li_2O and Li_2CO_3, which function as extraction materials. Subsequently, these substances undergo further processing to isolate lithium in its elemental state (Jose, S. A. et al., 2024). It is essential to acknowledge that the recycling rate may fluctuate based on the specific types of batteries and the processing techniques utilized. For example, Table 3 demonstrates the variations in recycling rates that arise from different processing methods applied to cathode materials such as $LiNiMnCoO_2$, $LiCoO_2$, and $LiCoNiO_2$ (Liu, P. et al., 2019; Zheng, Y. et al., 2019; Peng, C. et al., 2019; Tang, Y. et al., 2019; Shi, J. et al., 2019; Li, J. et al., 2016; Ren, G. et al., 2017).

Table 3. Pyrometallurgy process and operating conditions for spent LIB recovery processes

Cathode Material	**Pyrometallurgy Process**	**Additive**	**Condition**	**Separated Material**	**Recovery Rate (%)**	**Reference**
$LiNiMnCoO_2$	Reduction roasting and water and acid leaching(H_2SO_4)	Carbon	650 °C, 30 min	$LiCo_3$, Co, Li, NiO, MnO, CO_2(g)	Li: 93.67; Ni: 93.3; Co: 98.1; Mn: 99.5	(Liu, P. et al., 2019)
$LiNiMnCoO_2$	Plasma spray pyrolysis	-	600 °C	Regenerated $LiNiMnCoO_2$		(Zheng, Y. et al., 2019)
$LiCoO_2$	Nitration roasting and water leaching	NHO_3	250 °C, 60 min	$LiNO_3$, $Co(NO_3)_2$, NO(g), H_2O(g)	Li: 93; Co: 92.9; Ni: 92.9; Cu: 92.9	(Peng, C. et al., 2019)
$LiCoO_2$	Vacuum pyrolysis and water leaching	Carbon	600 °C	Co, CoO, $LiCO_3$, CO_2	Li: 93, Co: 99	(Tang, Y. et al., 2019)
$LiCoO_2$	Sulfation roasting and water leaching	SO_2(g)	700 °C, 120 min	Li2SO_4, $Li_2Co(SO_4)_2$, CoO, O_2(g)	Li: 99.5; Co: 17.4	(Shi, J. et al., 2019)
$LiCoO_2$	Oxygen-free roasting and wet magnetic separation	Carbon	1000 °C, 30 min	$LiCO_3$, Co	Li: 98.93; Co: 95.72	(Li, J. et al., 2016)
$LiCoNiO_2$	Carbothermic reduction smelting, manual separation of slag and alloy communication	NH_4CI	1450 °C, 30 min	Co, Ni, Cu, and Fe Alloy and slag FeO, SiO_2, AI_2O_3, CaO, MgO	Ni: 98.4; Co: 98.8; Cu: 93.6	(Ren, G. et al., 2017)

In recent years, traditional pyrometallurgy has experienced ongoing enhancements, and initiatives have been undertaken to incorporate it with alternative methodologies. Windisch-Kern et al. conducted a study on the lithium removal rates utilizing two distinct types of reactors, with the aim of enhancing the management of waste lithium-ion batteries. During the processing of lithium cobalt oxide, a lithium removal rate of 76% was attained utilizing Al_2O_3 crucibles following exposure to gas flow. The elevated purity achieved after this processing facilitates subsequent treatment procedures. The utilization of MgO crucibles can achieve a lithium removal rate of up to 97% (Windisch-Kern, S., Ponak, C. & Raupenstrauch, H., 2021). Öfner, W. et al. integrated pyrometallurgical techniques with hydraulic mechanical pretreatment to effectively eliminate suspended solids, thereby decreasing the carbon content from 33 wt.% to 19.23 wt.%. This innovative approach yielded a high-purity mixture of active materials suitable for lithium batteries, and subsequent pyrometallurgical processing produced a lithium-free metal alloy (Holzer, A. et al., 2022). These techniques have the potential to improve the purity of recycled metals.

Lithium exhibits a pronounced oxytropism, which ultimately leads to the formation of slag during the process of pyrometallurgy. The InduRed reactor, as proposed by Holzer et al., presents a viable solution to this challenge.

The researchers conducted an investigation into the performance of nickel-rich cathode materials and black mass under reducing conditions, utilizing heated microscopic experiments, thermogravimetric analysis, and differential scanning calorimetry. In a subsequent series of experiments, the investigations conducted within the InduRed reactor were further employed to examine the transferable coefficients of metals. The findings demonstrate that within the reaction temperature range of 800°C to 1,000°C, nickel, cobalt, and manganese display considerable recovery potential, while the slagging of lithium is substantially reduced (Windisch-Kern, S. et al., 2021).

3.3 Hydrometallurgy

Hydrometallurgy is a metallurgical technique that utilizes solvents and chemical reactions to facilitate the extraction of metals from mineral sources or waste materials. In the domain of lithium battery recycling, hydrometallurgy predominantly pertains to the methodology of extracting metallic materials from spent lithium batteries utilizing chemical solvents, with the objective of recovering valuable metals. Hydrometallurgy offers several benefits over pyrometallurgy, including enhanced recovery rates, improved product purity, and reduced energy consumption. Concurrently, hydrometallurgy poses certain challenges, notably the significant consumption of water resources. While hydrometallurgy does not emit significant volumes of exhaust gases, it has the potential to produce substantial quantities of wastewater during the recovery process, which could pose an environmental concern. The current challenges encountered in hydrometallurgy include equipment corrosion arising from the leaching process and diminished material adaptability. These issues underscore the need for further optimization of the process (Villen-Guzman, M. et al., 2024; Lv, W. et al., 2018). Hydrometallurgy can be further divided into various procedures, including, but not limited to, acid leaching, alkaline leaching, and bioleaching. Figure 4 provides a comprehensive depiction of the hydrometallurgical process, delineating the essential steps involved in the extraction of lithium salts from the solution. (Neumann, J. et al., 2022)

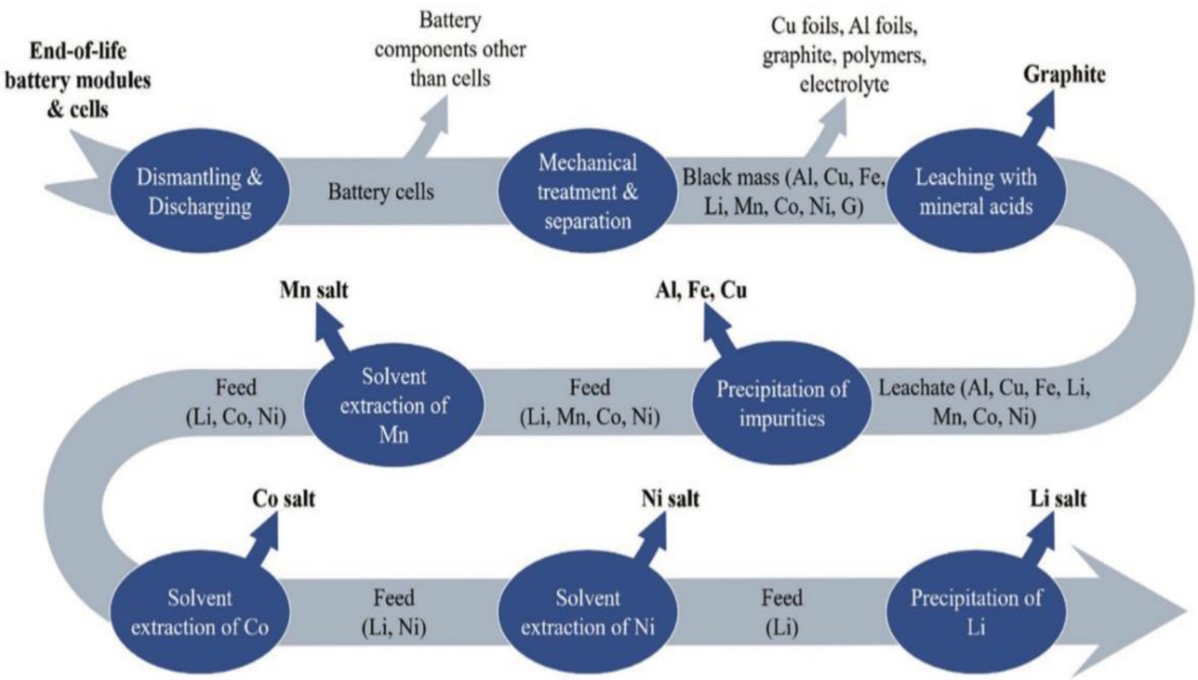

Figure 4. Overview about traditional hydrometallurgical processing

3.3.1 Acid Leaching

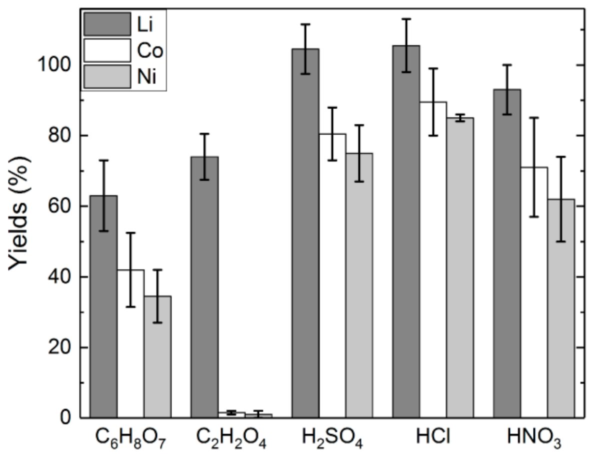

Figure 5. Metal recovery efficiency of different acids after adding hydrogen peroxide

Acid leaching can be categorized into two distinct types based on the nature of the acid utilized: inorganic acid leaching and organic acid leaching. Aaltonen et al. conducted a study to examine the leaching efficiency of different types of acids. As shown in the following figure, Figure 5 illustrates the metal recovery efficiency of various acids when hydrogen peroxide is employed as a reducing agent, while Figure 6 showcases the metal recovery efficiency of different acids in the absence of hydrogen peroxide. The recovery rates associated with inorganic acids typically surpass those of organic acids. Particularly, sulfuric acid and hydrochloric acid have been proven to be the most effective methods for leaching lithium from lithium-ion batteries (LIBs). Conversely, the efficacy of the reducing agents is prioritized in descending order as follows: ascorbic acid ($C_6H_8O_6$), D-glucose, and trioxidane (H_2O_3).

The extraction efficiency is optimized when a 10% solution of ascorbic acid is employed in conjunction with sulfuric acid (Aaltonen, M. et al., 2017).

While organic acids may not possess the same level of potency as inorganic acids, Fatima et al. effectively extracted nearly all valuable metals from the solution by submerging discarded lithium batteries in citric acid, which functioned as a chelating agent, and ascorbic acid, which served as a reducing agent. This technique presents an innovative and environmentally sustainable method for utilizing organic acid reagents (Fatima, S. et al., 2024). While organic acids are considered more environmentally sustainable and do not emit toxic gases, their elevated cost presents significant challenges for their application in industrial settings. (Wei, Y. F. et al., 2023)

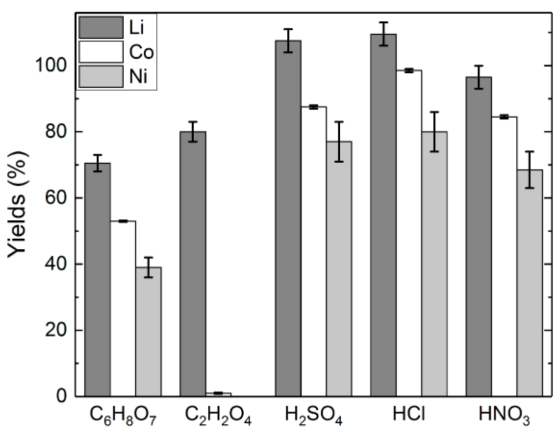

Figure 6. Metal recovery efficiency of different acids without adding hydrogen peroxide

3.3.2 Alkaline Leaching

Alkaline leaching, commonly known as ammonia leaching, utilizes ammonia water as a leaching agent to selectively recover valuable metals from the cathode materials of spent lithium-ion batteries. The fundamental principle of this process is that ammonia (NH_3), in an alkaline medium, can engage in complexation reactions with various metals. The primary benefit of this method lies in its capacity to selectively extract the desired metal; however, it exhibits a lower level of efficiency (Pan, Y. L. et al., 2024). Wang et al. conducted a leaching process on nickel-cobalt slag utilizing a solution composed of ammonia and ammonium sulfite hydrate. Under ideal conditions, the nickel leaching rate achieves 90.09%, while the cobalt leaching rate reaches 89.24%. This discovery presents a new methodology for alkaline leaching (Wang, Y. et al., 2022). In comparison to alternative processes, alkaline leaching, although facilitating selective leaching, demonstrates a reduced leaching rate, produces elevated temperatures during the reaction, and presents difficulties in the recovery of the leachate (Wei, Y. F. et al., 2023).

3.3.3 Bioleaching

Bioleaching refers to the process of employing the metabolic activities of microorganisms to engage with lithium battery powder in a leaching system, thereby promoting the dissolution and recovery of metallic elements. Biological leaching provides a superior recovery rate, reduced energy consumption, and is more environmentally sustainable in comparison to alternative hydrometallurgical techniques. Additionally, it functions independently of industrial machinery and does not require extreme reaction conditions. While bioleaching represents a highly promising recycling technique with the potential to develop into an environmentally friendly and sustainable recycling technology, it currently faces several challenges, including low efficiency, demanding leaching conditions, and prolonged cultivation periods (Zanoletti, A. et al., 2024). The key determinants affecting bioleaching encompass the selection of microbial strains (such as bacteria and fungi), leaching conditions (e.g., leaching methodologies, temperature, and the solid-liquid ratio), and cultivation conditions (e.g., culture media and nutrient substances) (Lü, M. Y. et al., 2023).

Boyden et al. identified an acidophilic chemolithoautotrophic organism from the sediments of a severely metal-contaminated acid mine lake. The study involved culturing this organism on agar plates supplemented with iron, sulfur, or a combination of both. The organism exhibited the highest growth and oxidation rates, alongside the lowest microbial diversity, and demonstrated a gradual adaptation to environments with escalating concentrations of metal ions. Ultimately, it achieved a recovery rate of up to 100% for lithium, cobalt, nickel, manganese, and aluminum (Boyden, L. M. et al., 2021). Microorganisms may exhibit a reduction in metabolic activity when exposed to elevated concentrations of metal ion solutions, potentially leading to a decreased rate of processing. Zhao et al. have put forth a methodology aimed at alleviating microbial stress induced by light metal ions through the incorporation of chemical agents (such as spermine and glutathione). Furthermore, they have recommended the application of electrochemical measurement techniques (e.g., Tafel scanning) to assess the health status of microorganisms (Zhao, C. et al., 2020).

3.4 Bio-Metallurgy

Bio-metallurgy is defined as the process of extracting metals from waste materials and minerals utilizing microorganisms and their metabolic byproducts. This technique is frequently utilized for the leaching of copper sulfide ores, the extraction of uranium mines and rare earths, and the oxidation pretreatment of refractory gold ores. It represents a vital method for advancing green and sustainable development within the metallurgy sector (Yang, B. J. et al., 2024). In comparison to alternative extraction methods, bio-metallurgy is characterized by a slower processing rate. Nevertheless, it presents numerous advantages, such as reduced emissions, enhanced environmental sustainability, significant selectivity for metals, and lower processing costs. Specifically, pyrometallurgical costs are estimated to be between USD 100 and USD 200 per ton of ore, while hydrometallurgical costs range from USD 50 to USD 100 per ton of ore. In contrast, the costs associated with bio-metallurgy are approximately USD 20 to USD 50 per ton of ore. As illustrated in Table 4, bio-metallurgy demonstrates a significant recovery rate for the recovery of metals including copper, uranium, and gold. Nevertheless, it is essential to acknowledge that, while bioleaching exemplifies the potential of bio-metallurgy and although bio-metallurgy has been used in metal recovery for many years, the application of bio-metallurgy for lithium recovery is still relatively rare. This domain is still in its nascent stages and necessitates further investigation and advancement.

Table 4. Percentage of metals extracted from e-waste through Bio-hydro-metallurgy

Copper (Cu)	The recovery of Cu often ranges from 50% to over 90%, which depends on different situations. In some cases, the near-complete copper is possible.
Gold (Au)	The recovery of Gold is typically ranging from 60% to 90%, which will be affected by different effects, like the specific microbial strains employed.
Uranium(U)	The recovery of Uranium often can be significantly high, even exceeding 90%,
Cobalt (Co)	Extraction of Cobalt by bio-hydro-metallurgy can achieve recovery between 60% and 80% in

	certain cases.
Nickel (Ni)	The recovery of Nickel can range from 50% to 80%.
Zinc (Zn)	The recovery of Zinc can range from 70% to 90%.
Silver (Ag)	The recovery of Silver can range from 50% to 90%.

4. Conclusions: Future Perspective of the Research

In summary, there exist various methods for recycling lithium, with the predominant techniques involving the extraction of lithium from lithium slag and the recycling of discarded lithium batteries. Each recycling technique presents distinct advantages and disadvantages, necessitating the selection of the most suitable method according to particular requirements. Pyrometallurgy is well-suited for the large-scale processing of batteries or slag, whereas hydrometallurgy offers the highest recovery rate, rendering it especially efficient for the extraction of precious metals. The continuous advancement of technology has given rise to the development of efficient and environmentally sustainable recycling methods, which facilitate the efficient recovery of rare and precious metals from power batteries. This progress contributes to a reduction in reliance on primary resources. It is expected that the industry will experience sustained growth over the next five years, with market size forecasts indicating an increase from approximately RMB 36.6 billion in 2023 to RMB 68.6 billion by 2027. This growth is projected to yield a compound annual growth rate (CAGR) of nearly 13.38%. This suggests that the market for recycling used lithium-ion batteries possesses considerable potential for growth. Future research endeavors concerning the recycling of used lithium batteries will focus on the development of innovative processes to overcome the technical challenges associated with a single treatment method. Additionally, this research will necessitate the integration of both chemical and physical methodologies to ensure effective processing. The market's exceptionally efficient recycling model is expected to facilitate the development of new technologies to a certain degree. As processes are continually refined in the future, additional industrial systems for the recycling of power batteries will be established. Concurrently, traditional methods will also undergo continuous enhancements to address existing challenges.

In conclusion, the recycling of utilized lithium-ion batteries is crucial for environmental protection and the circular use of resources. Given the advancements in technology and the rising demand in the market, this sector is positioned to encounter significant growth opportunities.

References

Aaltonen, M., Peng, C., Wilson, B. P. and Lundstrom, M., (2017). Leaching of Metals from Spent Lithium-Ion Batteries. *Recycling*, *2*(4), 20. https://doi.org/10.3390/recycling2040020.

Bae, H., Kim, Y., (2021). Technologies of lithium recycling from waste lithium-ion batteries: a review. *Materials Advances*, *2*, 3234-3250. https://doi.org/10.1039/d1ma00216c.

Bae, H., Kim, Y., (2021). Technologies of lithium recycling from waste lithium-ion batteries: A review. *Materials Advances*, *2*(11), 3234-3250. https://doi.org/10.1039/D1MA00216C.

Boyden, L. M. et al., (2021). Metal recovery from spent lithium-ion batteries via two-step bioleaching using adapted chemolithotrophs from an acidic mine pit lake. *Frontiers in Environmental Science*, https://www.frontiersin.org/articles/10.3389/fenvs.2021.635073/full.

Duan, X., Zhu, W., Ruan, Z., Xie, M., Chen, J. and Ren, X., (2022). Recycling of Lithium Batteries — A Review. *Energies*, *15*(5), 1611. https://doi.org/10.3390/en15051611.

Ekberg, C., Petranikova, M., (2015). *In Lithium Process Chemistry* (Eds.: A. Chagnes, J. Światowska), Elsevier, Amsterdam, 233-267.

Energy & Environmental Science, (2021). Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. DOI: 10.1039/D1EE00691F. Retrieved from https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee00691f.

Fatima, S., Khosa, M. K., Noor, A., Qayyum, S. and El Oirdi, M., (2024). Hydrometallurgical Extraction of Valuable Metals by Mixed Acid Leaching System for Used Lithium-Ion Batteries. *Sustainability*, *16*(16), 6817. https://doi.org/10.3390/su16166817.

Holzer, A., Zimmermann, J., Wiszniewski, L., Necke, T., Gatschlhofer, C., Öfner, W. and Raupenstrauch, H., (2022). A combined hydro-mechanical and pyrometallurgical recycling approach to recover valuable metals from lithium-ion batteries avoiding lithium slagging. *Batteries*, *9*(1), 15.

Hu, L. Q., (2022). Research on resource value and environmental hazards of spent lithium-ion batteries: A review of New Technologies for Recycling Spent Lithium-ion Batteries. *Battery Bimonthly*, *52*(5), 601-602.

https://doi.org/.

IEA, (2024). Global EV Outlook 2024, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2024, Licence: CC BY 4.0

IEA, (2024). Quarterly electric car sales by region, 2021-2024, IEA, Paris. https://www.iea.org/data-and-statistics/charts/quarterly-electric-car-sales-by-region-2021-2024, Licence: CC BY 4.0

International Energy Agency (IEA), (2022). Global EV Outlook 2022, International Energy Agency, Accessed on October 6, 2024, from https://www.iea.org.

Jose, S. A., Stoll, J. L., Smith, T., Jackson, C., Dieleman, T., Leath, E., Eastwood, N. and Menezes, P. L., (2024). Critical Review of Lithium Recovery Methods: Advancements, Challenges, and Future Directions. *Processes*, *12*(10), 2203. https://doi.org/10.3390/pr12102203.

Kalak, T., Tachibana, Y., (2021). Removal of lithium and uranium from seawater using fly ash and slag generated in the CFBC technology. *RSC Advances*, *11*, 21964-21978.

Katwala, A., (2018). The spiralling environmental cost of our lithium battery addiction. Wired, https://www.wired.co.uk/article/lithium-batteries-environment-impact.

Kim, S., Bang, J., Yoo, J., Shin, Y., Bae, J., Jeong, J., ... and Kwon, K., (2021). A comprehensive review on the pretreatment process in lithium-ion battery recycling. *Journal of Cleaner Production*, *294*, 126329.

Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, V., Elliott, R. J., Heidrich, O., ... and Offer, G., (2021). Financial viability of electric vehicle lithium-ion battery recycling. *iScience*, *24*(7).

Li, J., Huang, S., (2020). Recycling of lithium slag as a green admixture for white reactive powder concrete. *Journal of Material Cycles and Waste Management*, *22*(6), 1818-1827.

Li, J., Wang, G. and Xu, Z., (2016). Environmentally-Friendly Oxygen-Free Roasting/Wet Magnetic Separation Technology for in Situ Recycling Cobalt, Lithium Carbonate and Graphite from Spent LiCoO2/Graphite Lithium Batteries. *J. Hazard. Mater*, 302, 97-104.

Liu, C. Y., Lu, J. S., (2023). Research progress on physicochemical characteristics and resource utilization of lithium slag. *Chemical Minerals and Processing*, *52*(6), 56-64. https://doi.org/.

Liu, P., Xiao, L., Tang, Y., Chen, Y., Ye, L. and Zhu, Y., (2019). Study on the Reduction Roasting of Spent LiNixCoyMnzO2 Lithium-Ion Battery Cathode Materials. *J. Therm. Anal. Calorim*, *136*, 1323-1332.

Lü, M. Y., Deng, X. Y., Gong, S. L. and Li, J. Y., (2023). Research progress on bioleaching for recycling spent lithium-ion batteries. *Battery Bimonthly*, *53*(5), 563-567. https://doi.org/10.19535/j.1001-1579.2023.05.021.

Lv, W., Wang, Z., Cao, H., Sun, Y., Zhang, Y. and Sun, Z., (2018). A critical review and analysis on the recycling of spent lithium-ion batteries. *ACS Sustainable Chemistry & Engineering*, *6*(2), 1504-1521. https://doi.org/10.1021/acssuschemeng.7b03811.

Mei, Y. R., Liu, L. M., Chen, R., Hou, H. J., Hu, J. P. and Yang, J. K., (2024). Research progress on recovery and high-value utilization of valuable metals from cathode materials of spent lithium-ion batteries. *Energy Environmental Protection*, 1-12. https://doi.org/10.20078/j.eep.20240609

Neumann, J., Petranikova, M., Meeus, M. and Gamarra, J. D. et al., (2022). Adv. *Energy Mater*, *12*, 2102917.

Neumann, J., Petranikova, M., Meeus, M., Gamarra, J. D., Younesi, R., Winter, M. and Nowak, S., (2022). Recycling of lithium-ion batteries — current state of the art, circular economy, and next generation recycling. *Advanced energy materials*, *12*(17), 2102917.

Pan, Y. L., Lu, J. W., Zheng, L. X., Zhen, A. G., Qiu, C., Yang, Y. S., ... and Zheng, H. J., (2024). Progress in hydrometallurgical recycling processes for spent lithium-ion batteries. *Zhejiang Chemical Industry*, *55*(7), 31-36. https://doi.org/.

Peng, C. Liu, F. Wang, Z. Wilson, B.P. and Lundstrom, M., (2019). Selective Extraction of Lithium (Li) and Preparation of Battery Grade Lithium Carbonate (Li2CO3) from Spent Li-Ion Batteries in Nitrate System. *J. Power Sources*, *415*, 179-188.

Ren, G., Xiao, S., Xie, M., Pan, B., Chen, J., Wang, F. and Xia, X., (2017). Recovery of Valuable Metals from Spent Lithium Ion Batteries by Smelting Reduction Process Based on FeO-SiO2-Al2O3 Slag System. *Trans. Nonferrous Met. Soc. China*, *27*, 450-456.

Shi, J., Peng, C., Chen, M., Li, Y., Eric, H., Klemettinen, L., Lundstrom, M. and Taskinen, P., Jokilaakso, A., (2019). Sulfation Roasting Mechanism for Spent Lithium-Ion Battery Metal Oxides Under SO2-O2-Ar Atmosphere. *JOM*, *71*, 4473-4482.

Tadesse, B., Makuei, F., Albijanic, B. and Dyer, L., (2019). The beneficiation of lithium minerals from hard rock ores: A review. *Miner. Eng*, *131*, 170-184.

Tang, Y. Xie, H. Zhang, B. Chen, X. Zhao, Z. Qu, J. Xing, P. and Yin, H., (2019). Recovery and Regeneration of LiCoO2-Based Spent Lithium-Ion Batteries by a Carbothermic Reduction Vacuum Pyrolysis Approach: Controlling the Recovery of CoO or Co. *Waste Manag*, *97*, 140-148.

Torabian, M. M., Jafari, M. and Bazargan, A., (2021). Waste Manage. *Res*.

Toro, L., Moscardini, E., Baldassari, L., Forte, F., Falcone, I. and Coletta, J., (2023). A systematic review of battery recycling technologies: Advances, challenges, and future prospects. *Energies*, *16*(18), 6571. https://doi.org/10.3390/en16186571.

Villen-Guzman, M., Vereda-Alonso, C., Rodriguez-Maroto, J.M. and Paz-Garcia, J.M., (2024). Towards Sustainable Lithium-Ion Battery Recycling: Advancements in Circular Hydrometallurgy. *Processes*, *12*(7), 1485. DOI: 10.3390/pr12071485.

Wang, X., Wang, H. and Wang, Q., (2022). Research progress on resource utilization of lithium slag in China. *Materials Reports*, *36*(24), 59-69. https://doi.org/.

Wang, Y., Xu, Z., Zhang, X., Yang, E. and Tu, Y., (2022). An ammonia leaching process for the recovery of valuable metals from nickel and cobalt slag. *JOM*, *74*(11), 3006-3015. https://doi.org/10.1007/s11837-022-05295-x.

Wei, Y. F., Luo, F. M., Wu, Y. X., Wu, N., Zhang, C. X. and Xiang, X. Y., (2023). Research progress on recovery of valuable metals from cathode materials of retired lithium-ion batteries. *Jiangxi Metallurgy*, *43*(3), 204-212. https://doi.org/10.19864/j.cnki.jxye.2023.03.005.

Windisch-Kern, S., Holzer, A., Ponak, C. and Raupenstrauch, H., (2021). Pyrometallurgical lithium-ion-battery recycling: Approach to limiting lithium slagging with the InduRed reactor concept. *Processes*, *9*(1), 84. https://doi.org/10.3390/pr9010084.

Windisch-Kern, S., Ponak, C. and Raupenstrauch, H., (2021). A Novel Pyrometallurgical Recycling Process for Lithium-Ion Batteries and Its Application to the Recycling of LCO and LFP. *Metals*, *11*(1), 149.

Wojciech Mrozik, Mohammad Ali Rajaeifar, Oliver Heidrichab and Paul Christensen, (2021). Environmental impacts, pollution sources, and pathways of spent lithium-ion batteries. *Energy & Environmental Science*.

Yang, B. J., Liu, Y., Liu, H. C., Li, Y. M., Gan, M., Wang, J., ... and Qiu, G. Z., (2024). Research status and development trends of biohydrometallurgy technology. *Journal of Biology*, *41*(3), 1-10. https://doi.org/.

Yao, L. P., Zeng, Q., Qi, T. and Li, J., (2020). An environmentally friendly discharge technology to pretreat spent lithium-ion batteries. *Journal of Cleaner Production*, *245*, 118820.

Zanoletti, A., Carena, E., Ferrara, C. and Bontempi, E., (2024). A Review of Lithium-Ion Battery Recycling: Technologies, Sustainability, and Open Issues. *Batteries*, *10*(1), 38. https://doi.org/10.3390/batteries10010038.

Zhai M., Zhao J. and Wang D., (2017). Applying lithium slag powders to cement-based materials as supplementary cementitious component: an overview. *Mater Rev*, *31*, 139-144.

Zhang, H., Han, Y. and Lai, J. et al., (2024). Direct extraction of lithium from ores by electrochemical leaching. *Nat Commun*, *15*, 5066. https://doi.org/10.1038/s41467-024-48867-0.

Zhao, C. et al., (2020). Advances in bioleaching of waste lithium batteries under metal ion stress. *Bioresources and Bioprocessing*. https://bioresourcesbioprocessing.springeropen.com/articles/10.1186/s40643-020-00335-1.

Zhao, G. J., Liang, T. R., Hu, Y. X. and Xu, J., (2024). Overview of recycling technologies for spent lithium-ion batteries. *Chinese Journal of Power Sources*, *48*(11), 2111-2120. https://doi.org/.

Zheng, Y., Wang, S., Gao, Y., Yang, T., Zhou, Q., Song, W., Zeng, C., Wu, H., Feng, C. and Liu, J., (2019). Lithium Nickel Cobalt Manganese Oxide Recovery via Spray Pyrolysis Directly from the Leachate of Spent Cathode Scraps. ACS Appl. *Energy Mater*, *2*, 6952-6959.