附表 1　不同吸附剂吸附性能比较

Appendix 1　Comparison of adsorption properties of different adsorbents

吸附剂/前驱体	卤水	锂浓度(g/L)	镁锂比值	吸附能力(mg/g)	吸附平衡时间(h)	洗脱效率(%)	溶损率(%)/n 循环	锂回收率(%)	参考文献
$LiCl \cdot 2Al(OH)_3 \cdot mH_2O$	—	0.8	135.2	20.7	—	—		—	Kotsupalo et al.,2013
磁性铝盐吸附剂 MASA	察尔汗盐湖卤水	0.35	892.14	4～5	1	>90	0/5	—	陈程等, 2018
MLDHs	察尔汗盐湖卤水	0.397	284	5.83	—	—		—	Chen Jun et al.,2020
$C\text{-}LiCl \cdot 2Al(OH)_3 \cdot nH_2O$	察尔汗盐湖卤水	0.399	301.5	4.9	50	—		—	张瑞等, 2021
铝基锂吸附剂	泰和地下卤水	0.07	8.71	15.06	—	93.69		—	程鹏高等, 2021
G-Li/Al-LDH	察尔汗盐湖卤水	0.399	301.5	4.92	—	82.2	0/30	—	钟静等, 2021
$LiCl \cdot 2Al(OH)_3 \cdot mH_2O$	盐湖老卤	1.21	91.76	6～7	—	—		92	张绍成等, 2004
Li/Al-LDH	察尔汗盐湖卤水	0.399	301.5	7.26	2	—	3.58/12	72.2	Zhong Jing et al.,2021
$LiMn_2O_4$/NF	乌尔米亚湖卤水	—	—	62	—	>96	Mn:1.15/3	—	Zandevakili et al.,2014
$Li_4Mn_5O_{12}$/PAM	—	—	—	18.61	—	—	Mn:0/30	—	Xiao Jiali et al.,2015b
$Li_4Mn_5O_{12}$/EP	—	—	—	33.6	—	98.5	Mn:0.12/30	93.2	Lai Xianrong et al.,2020
$Li_4Mn_5O_{12}$	—	—	—	45.81	—	—	Mn:0.07	—	孙淑英等, 2010
$Li_4Mn_5O_{12}$	察尔汗盐湖卤水	0.179	746	2.79	—	—	/55	—	Xiao Jiali et al.,2015a
$Li_{1.6}Mn_{1.6}O_4$	察尔汗盐湖卤水	—	374	31.44	—	—		97	孟庆伟等, 2017
$Li_{1.6}Mn_{1.6}O_4$/PVC	—	—	—	29	6	95	Mn:3.50	—	解利昕和陈小棉, 2013
$Li_{1.6}Mn_{1.6}O_4$	—	—	—	34.17	48	—	Mn:<5	—	王禄等, 2007
$Li_{1.6}Mn_{1.6}O_4$	—	0.26	398.87	27.15	—	73.66/10	Mn:<2.5	85	Shi Xichang et al.,2011
PVDF-$Li_{1.6}Mn_{1.6}O_4$	—	—	—	41	12	95	Mn:3.50	—	解利昕和陈小棉, 2014
$Li_{1.6}Mn_{1.6}O_4$	—	0.25	431.9	20	—	96.28	Mn:7.46	—	石西昌等, 2013
$Li_{1.6}Mn_{1.6}O_4$/FO	—	—	—	29.33	—	65.02/5	Mn:6.22;Fe:4.14	—	Xue Feng et al.,2019
$Li_{1.33}Fe_xMn_{1.67\text{-}x}O_4$	—	1.63	17.79	28	—	90	Mn: 0.7/4	—	Chitrakar et al.,2014a
$Li_{1.6}Al_xMn_{1.6\text{-}x}O_4$	—	—	—	32.6	—	82.21/4	Mn: 1.92/4	—	Zhang Guotai et al.,2019
$Li_{1.6}Mn_{1.6}O_4$	—	—	—	27.6	—	86.59/4	Mn: 2.06/4	—	Zhang Guotai et al.,2019
$Li_{1.6}Mn_{1.6}O_4$/PAN	—	—	—	17.53	—	>96/10	Mn:0.68～1.58/5～8	—	Park et al.,2014
H_xTiO_3	大柴旦盐湖卤水	1.95	53.85	36.34	24	96.04/3		—	Wang Shulei et al.,2017
Li_2TiO_3	—	—	—	49.38	—	78.9	Ti:<0.07	—	Zhang Liyuan et al.,2016
Li_2TiO_3	乌尤尼盐湖	1.63	17.79	32.6	—	98		—	Chitrakar et al.,2014b
Li_2TiO_3	西台吉乃尔盐湖	0.67	103.8	24.5	—	98.12/5	Ti:<0.06	—	Gu Donglei et al.,2018
Li_2TiO_3/3D	—	—	—	76.3	—	—	Ti:<0.5	—	Xu Xin et al.,2017
$H_4Ti_5O_{12}$	合成溶液	5	—	32.39	—	96.8	Ti:<1	—	颜辉等, 2014
$H_4Ti_5O_{12}$/3DOM	—	—	—	56.7	—	94	Ti:<0.26	—	董殿权等, 2012
$H_4Ti_5O_{12}$/NF	—	—	—	59.1	—	86.5/6	Ti:<1/3	—	Wei Shudan et al.,2020

附表 2 不同萃取体系的萃取条件和效果比较

Appendix 2 Comparison of extraction conditions and effects of different extraction systems

卤水	锂浓度(g/L)	镁锂比值	萃取体系	萃取条件	锂萃取率(%)/级数	锂反萃率(%)	参考文献
合成卤水	0.2	534.15	TBP-BA-$FeCl_3$-260#磺化煤油	pH=2, $n(Fe^{3+}/Li^{+})=3.0$, $T=20℃$	90/1	—	李锦丽等，2014
合成卤水	1.416	66.09	75%TBP-煤油-$FeCl_3$	O/A=1.5, $n(Fe^{3+}/Li^{+})=2$, $c(H^{+})=0.02$ mol/L, $t=20$ min	88/1	60/1	孙淑英等，2011
青海某盐湖老卤	1.67	68.56	30%TBP-20%NX-磺化煤油-$FeCl_3$	O/A=1.5, $n(Fe^{3+}/Li^{+})=2$, $c(H^{+})=0.05$ mol/L, $t=15$ min	89.19/1	80.08/1	蒋应平等，2021
合成卤水	0.3	369	TBP-煤油-$FeCl_3$	O/A=1/7, $C_{TBP}=75\%$, $n(Fe^{3+}/Li^{+})=1.3$, $c(H^{+})=0.009$ mol/L	88.5/3	99/4	Shi Dong et al., 2019
青海盐湖老卤	0.4	304.5	30%TBP-磺化煤油	O/A=2, $n(Fe^{3+}/Li^{+})=1.8$, $c(H^{+})=0.1$ mol/L, $t=10$ min	75/1	51/1	张永兴等，2019
东台吉乃尔提钾老卤	0.79	5.26	80%TBP-磺化煤油-$FeCl_3$	O/A=2, $n(Fe^{3+}/Li^{+})=1.5$, $c(H^{+})=0.05$ mol/L, $t=5$ min	91.4/1	—	贾旭宏等，2011
察尔汗盐湖	0.05	94.78	40%TBP-$FeCl_3$-40%MIBK	O/A=1	99/5	100/3	Xiang Wei et al., 2017
合成卤水	0.35	25.71	30%TBP-70%琥珀酸二乙酯-$FeCl_3$	O/A=1, $n(Fe^{3+}/Li^{+})=1.3$	65/1	99.14/2	Zhou Zhiyong et al., 2020
青海盐湖提硼老卤	3.27	36.7	TBP-煤油-协萃剂 A-$FeCl_3$	O/A=1, pH=2, $n(Fe^{3+}/Li^{+})=1.25$, $T=20℃$	99.44/4	—	张丽芬等，2021
卤水	1.96	40.06	40%TBP-20% EB-$FeCl_3$-40%煤油	O/A=2/1, $c(H^{+})=0.05$ mol/L; $n(Fe^{3+}/Li^{+})=1.5$	87.12/1	90/1	石成龙等，2020
西台吉尔除硼老卤	5.02	21.53	40%TBP-$FeCl_3$-30%P507	O/A=1, $n(Fe^{3+}/Li^{+})=4$; $t=20$ min, $T=293$ K	99.8/3	99.81/3	Su Hui et al., 2020
卤水	2.604	41.55	40%TBP-$FeCl_3$-20%DOP	O/A=2, $c(HCl)=0.05$ mol/L, $t=10$ min	99.5/3	97.98/3	Ji Lianmin et al., 2016
大柴旦盐湖老卤	2.21	45.57	TBP-$NaClO_4$	O/A=2, $n(ClO_4^{-}/Li^{+})=2$, pH=5～8, $t=10$ min, $T=20℃$	97.23/3	81.52	杨立新等，2013
合成卤水	0.141	29.36	20%N503-20%TBP-200#煤油	$c(Cl^{-})>8$ mol/L, $c(H^{+})=0.02$ mol/L, $n(Fe^{3+}/Li^{+})=1.6$	90	89	许仁庆，1979
青海盐湖提钾老卤	0.298	15.36	N523-30%TBP-50%磺化煤油	O/A=2, $c(H^{+})=0.05$ mol/L, $n(Fe^{3+}/Li^{+})=1.3$	99.5/3	>99/2	时东等，2013
东台吉乃尔盐湖老卤	2.32	49.07	N523-TBP-$FeCl_3$	O/A=2, $c(H^{+})=0.04$ mol/L, $n(Fe^{3+}/Li^{+})=1.43$	97.05	99/3	Shi Dong et al., 2018
卤水	0.138	33.24	HBTA-TOPO	O/A=1.5, pH=11.2, $c(HBTA)=0.05$ mol/L, $c(TOPO)=0.1$ mol/L, $c(LiCl)=0.5$ mol/L, $T=25℃$	97	95	Zhang Licheng et al., 2017
卤水	—	—	HBTA-TOPO-煤油	O/A=1, $T=25℃$	97/3	97	李丽娟等，2018
沉锂母液	2	—	HBTA-TOPO-煤油	O/A=1, $c(HBTA)=0.4$ mol/L, $c(TOPO)=0.3$ mol/L, $T=25℃$	95	—	Zhang Licheng et al., 2018

附表 3　不同膜镁锂分离效果及其稳定性比较

Appendix 3　Comparison of separation effect and stability of magnesium and lithium with different membranes

膜	膜材料	Li^+浓度 (mol/L)	Li/Mg 分离系数	Li^+扩散系数 ($mol/cm^2/s$)	Mg^{2+}扩散系数 ($mol/cm^2/s$)	稳定性(天)	参考文献
PES/SPEEK	聚醚砜,磺化聚醚醚酮	0.13	—	1.67×10^{-8}	—	50	Song Jianfeng et al.,2014
SPEEK-HMO	SPEEK,HMO	0.2	3.1	8.99×10^{-8}	4.4×10^{-8}	—	Zhang Jie et al.,2019
EVAL	嵌段共聚物(聚乙烯醇)	0.1	>300	2.7×10^{-8}	—	43.21	Xing Lixin et al.,2016
PIM:TTA-TOPO-CTA	噻吩酰三氟丙酮,三辛基膦氧化物,三醋酸纤维素	0.0029	—	0.03×10^{-8}	—	—	Cai Chunqing et al.,2019
PEEK	甲烷磺酸,硫酸	0.1	—	2.5×10^{-8}	—	21	Huang Tao et al.,2019
PIM:PVC-cTBP	TBP,$FeCl_3$,PVC	0.2	176	0.22×10^{-10}	0.19×10^{-11}	3	Zhang Chengyi et al.,2020b
SLM:PVDF-[C4mim][NTf2]-TBP	1-丁基-3-甲基咪唑双(三氟甲基磺酰基)酰亚胺,磷酸三丁酯	0.088	1.66	7×10^{-7}	—	2	Zante et al.,2019
PVC@MOF	HSO_3-UiO-66	1	>4	2.0×10^{-10}	4.67×10^{-11}	78	Zhang Chengyi et al.,2020a

附表 4　不同纳滤膜卤水镁锂分离的最佳操作条件及表现比较

Appendix 4　The best operating conditions and performances comparison of magnesium lithium separation in brines with different nanofiltration membranes

纳滤膜	卤水	卤水浓度 (g/L)	初始镁锂比值	操作条件	纳滤后镁锂比值	锂回收率(%)	锂截留率 (%)/级数	镁截留率 (%)	参考文献
DK4040F	青海盐湖卤水	0.13～0.23	28.30～48.50	流速:4 L/min,压力 3.4 MPa	1.86～4.04	48.37～62.96	37.04～51.63/1	95.09～96.89	康为清等, 2014
DK1812	合成卤水	—	17～75	压力 3.5 MPa,pH=4.0,流速 225 $L/m^2/h$	0.5～4.3	35～70	30～65	>90	李燕等, 2021
NF90	合成卤水	0.141	10	pH=5,压力 0.8 MPa,流速=40 cm/s, T=20℃	0.19	—	66～77	>99	Pramanik et al.,2019
NF270	合成卤水	0.141	10	pH=5,压力 0.8 MPa,流速=40 cm/s, T=20℃	2.1	—	48～56	>91	Pramanik et al.,2019
NF3B02S	合成卤水	0.019	40	压力 0.8 MPa	0.9	85	—	96	Bi Qiuyan et al.,2014
NF14040	柴达木盐湖卤水	0.6～0.8	2.5～3.33	压力=2.5 MPa,流速=38 $L/m^2/h$, T=20℃,浓缩 8 倍	0.15	108.5*	—	94.7	邢红等, 2016
NF90	ChottDjerid 盐湖	0.06	56.76	压力=15 MPa,稀释 10 倍	—	—	15	100	Somrani et al.,2013

注:* 负截留现象可提高 Li^+ 回收率。

附表 5 电控离子交换提锂系统性能比较

Appendix 5 Performance comparison of lithium extraction with electrically switched ion exchange

电极系统	锂吸附容量(mg/g)	锂吸附能耗(Wh/mol)	纯度(%)	容量保留率(%)/n 循环	平衡时间(h)	镁锂分离系数	参考文献
λ-MnO_2/P_t	11	33	—	100/5	—	—	Kanoh et al.,1993
λ-MnO_2/AC	—	4.2	91.8	96/50	—	—	Kim et al.,2015
λ-MnO_2/Ag	7.34	21.3	99	—	17.4	—	Kim et al.,2019
λ-MnO_2/Ag	—	1	84.56	87/20	—	3.37	Lee et al.,2013
λ-MnO_2/Ag	—	4.1	61.3	—	—	—	Trócoli et al.,2017
λ-MnO_2/NiHCF	14.88	3.6	96.2	—	7.4	1700	Trócoli et al.,2017
λ-MnO_2/PPy/PS	35.2	—	—	98.9/5	2	—	Du Xiao et al.,2016
λ-MnO_2/3D 石墨毡	26.14	23.38	—	90.4/20	0.17	45.58	Mu Yingxin et al.,2021
λ-MnO_2/Ag	13.88	—	—	82.9/50	—	120.8	Liu Dongfan et al.,2018
3D-$LiMn_2O_4$/活性炭	12.84	1.41	97.37	91.66/30	—	—	Zhao Xiaoyu et al.,2020
AlZr-LMO/Ag	49.92	5.92	97.24	56.67/30	0.5	23.81	Luo Guiling et al.,2022
LMO/Ag	34.17	7.4	99.25	29.21/30	—	76.92	Luo Guiling et al.,2022
$LiMn_2O_4$/NiHC	—	6.1	94	—	—	—	Palagonia et al.,2020
$LiFePO_4$/Ag	8.19	1	84.56	—	—	—	Pasta et al.,2012
$LiFePO_4$/Ag	—	2.8	97.86	—	—	116	Trocoli et al.,2014
$LiFePO_4$/NiHCF	15.03	8.7	97.86	—	—	—	Trocoli et al.,2015
$H_{1.6}Mn_{1.6}O_4$/rGO	38.78	—	—	99/5	5	10.23	Wang Qiang et al.,2019
Tr-oh LMO/Ag	20.25	12.28	—	85/30	2	—	Zhou Guolang et al.,2023
$Li_{1-x}Ni_{1/3}Co_{1/3}Mn_{1/3}O_2$/Ag	10.83	2.6	96.4	96.9/20	0.33	397.63	Lawagon et al.,2018
$LiMn_2O_4$/PPy	39	—	—	—	—	—	Marchini et al.,2016
$LixMn_2O_4$/PANI	23.56	3.95	—	70.8/200	3.6	—	Zhao Along et al.,2019

附表 6 “摇椅式”电化学锂吸附能力比较

Appendix 6 Comparison of Li^+ adsorption capacity of “rocking chair” electrochemistry

电极系统	锂浓度(g/L)	初始溶液镁锂比值	锂吸附容量(mg/g)	锂吸附能耗(Wh/mol)	吸附溶液镁锂比值	锂回收率(%)	参考文献
$LiFePO_4$/AXM /$FePO_4$	0.22	60	41.26	—	0.45	—	Zhao Zhongwei et al.,2013b
$LiFePO_4$/$FePO_4$	0.22	493	24.1	—	0.3	—	Zhao Zhongwei et al.,2013a
$LiFePO_4$/IONAC MA3475/$FePO_4$	0.097	134.4	32	—	1.2	>85	He Lihua et al.,2018
$LiFePO_4$/IONAC MA3475/$FePO_4$	0.51	48.4	25	—	0.5	—	He Lihua et al.,2018
$LiFePO_4$/AXM/$FePO_4$	0.2	0	38.9	—	—	—	Liu Xuheng et al.,2015
$LiMn_2O_4$/ AXM /$Li_{1-x}Mn_2O_4$	0.6	0	22	18	—	22	Zhao Mengyao et al.,2017
$LiMn_2O_4$/AXM /λ-MnO_2	0.21	0	24.29	—	—	—	Liu Dongfan et al.,2019
$LiMn_2O_4$/IONAC MA3475/$Li_{1-x}Mn_2O_4$	1.91	60.99	17.2	8.74	1.08	—	Liu Dongfu et al.,2021
$LiMn_2O_4$/IONAC MA3475/$Li_{1-x}Mn_2O_4$	0.092	147.8	12	37	0.37	50～75	Xu Wenhua et al.,2021
$LiMn_2O_4$/IONAC MA3475/$Li_{1-x}Mn_2O_4$	2.05	58.8	15.7	16	1.7	83.3	Xu Wenhua et al.,2021

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