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Comprehensive Benefit Evaluation of Utilization and Disposal Technologies of Coal Chemical Waste Salts Based on the DANP-Cloud Model Framework

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Table S1. Overview of the investigated enterprises and correspondence between waste–salt samples, production processes, and saline wastewater treatment processes

Enterprise Code	Waste salt sample ID	Enterprise Type	Main Feedstock	Main Products	Saline Wastewater Treatment Process	Sampling Source / Salt Generation Unit	Waste Salt Output (× 10^4 t · a^{-1})	Waste Salt Treatment/Disposal Process
E1	WS1	Coal–to–liquids	Coal	Coal–based diesel, naphtha, long–chain hydrocarbons, LPG, methanol	Evaporation pond	Evaporation pond crystallized salt	24	Flexible landfill disposal
E2	WS2–1 WS2–2	Coal–based multi–industry chain deep processing	Coal	Coke, polyethylene, polypropylene, methanol, benzene, xylene, modified asphalt	Multi–effect evaporation, freeze crystallization	Two distinct waste–salt streams from independent saline wastewater treatment units	1.3	Rigid landfill disposal
E3	WS3	Coal–based multi–industry chain deep processing	Coal, semi–coke	Methanol, acetic acid, polyethylene, 1,4–butanediol, tetrahydrofuran	MVR	MVR crystallized salt	1	Rigid landfill disposal
E4	WS4	Coal–to–urea	Coal	Methanol, liquid ammonia, urea	MVR	MVR crystallized salt	0.5	Rigid landfill disposal
E5	WS5	Coal tar to needle coke	Coal tar	Needle coke, anthracene oil, kerosene	MVR	MVR crystallized salt	0.7	Rigid landfill disposal
E6	—	Petroleum–based olefin deep processing	Naphtha, LPG	Polyethylene, butadiene, mixed benzene, liquid ammonia, etc.	Discharged to E1 for treatment	—	—	—
E7	—	Coal–to–olefins	Coal	Polypropylene, coal–based gasoline, LPG, liquid ammonia, sulfur, ammonium sulfate	Discharged to E15 for treatment	—	—	—
E8	—	Coal–based methanol and downstream processing	Coal	Methanol, polyoxymethylene	Discharged to E15 for treatment	—	—	—

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Table S1. Overview of the investigated enterprises and correspondence between waste–salt samples, production processes, and saline wastewater treatment processes (continued)

Enterprise Code	Waste salt sample ID	Enterprise Type	Main Feedstock	Main Products	Saline Wastewater Treatment Process	Sampling Source / Salt Generation Unit	Waste Salt Output ($\times 10^4$ $t \cdot a^{-1}$)	Waste Salt Treatment/Disposal Process
E9	—	Coal–based fine chemicals deep processing	Coal	n–Butanol, octanol, neopentyl glycol	Discharged to E5 for treatment	—	—	—
E10	—	Coal–based oil products deep processing	Coal tar, condensate oil	Methyl tert–butyl ether (MTBE), crude benzene	Discharged to E16 for treatment	—	—	—
E11	—	Coal–based fine chemicals deep processing	Coal	Methanol, ethylene glycol, mixed monohydric alcohols	Discharged to E16 for treatment	—	—	—
E12	—	Coal tar deep processing	Coal tar	LPG, aromatic mixtures	Discharged to E16 for treatment	—	—	—
E13	—	Oil and gas deep processing	LPG	Methanol, mixed C4, naphtha, mixed aromatics	Discharged to E16 for treatment	—	—	—
E14	—	Propane deep processing	LPG	Propylene, polypropylene	Discharged to E16 for treatment	—	—	—
E15	WS15	Wastewater treatment and reuse	Mine water, coal chemical wastewater	Reclaimed water, regenerated NaCl, regenerated Na_2SO_4	MVR + freeze crystallization + thermal dissolution	Regenerated salt from centralized wastewater treatment and reuse system	0.17	Flexible landfill disposal
E16	WS16	Wastewater treatment and reuse	Coal chemical wastewater and wastewater from other industries	Reclaimed water	MVR	MVR crystallized salt from centralized wastewater treatment	0.7	Rigid landfill disposal

Table S2. Regional division of three-dimensional fluorescence spectra

Fluorescence region	Excitation - emission wavelength range (Ex/Em)	Assigned component
Region I	Ex: 200~250 nm, Em: 280~330 nm	Protein-like (tyrosine-like)
Region Ⅱ	Ex: 200~250 nm, Em: 330~380 nm	Protein-like (tryptophan-like)
Region Ⅲ	Ex: 200~250 nm, Em: 380~550 nm	Fulvic acid-like substances
Region Ⅳ	Ex: 250~400 nm, Em: 280~380 nm	Microbial by-product-like substances
Region Ⅴ	Ex: 250~400 nm, Em: 380~400 nm	Humic acid-like substances

Table S3. Typical cases of waste salt utilization and disposal technologies from six enterprises

Enterprise code	Project location	Main feedstock	Waste salt treatment technology	Main products after treatment
E1	Ningxia	Coal	(Concentrated brine) impurity removal and purification + evaporation and crystallisation (MVR + evaporation ponds); flexible landfill disposal of mixed salts	/
E5	Ningxia	High-temperature coal tar, coal tar, washing oil, etc.	(Concentrated brine) impurity removal and purification + evaporation and crystallisation (MVR); disposal of mixed salts via controlled landfilling	/
E15	Ningxia	Mine water, coal chemical wastewater	(Concentrated brine) impurity removal and purification + crystallisation and salt separation; regenerated salt sold externally, impure salt disposed of via flexible landfill	NaCl、Na2SO4
A	Jiangsu	Multi-industry waste salts from agriculture, pharmaceuticals, dyes, resins, etc.	Solid salt catalytic pyrolysis + dissolution + catalytic oxidation for impurity removal + evaporation and crystallisation for salt separation + thermal desorption of solid salt; the regenerated salt is sold, whilst the mother liquor is recycled after impurity removal	NaCl、Na2SO4
B	Henan	Waste salts from pharmaceutical and fluorochemical industries; sodium bicarbonate (external supply)	Sodium sulphate is used to produce baking soda via double decomposition and the ammonium carbonate cycle, with ammonium sulphate produced as a by-product; the salt is sold externally, whilst the mother liquor is recycled after impurity removal.	Sodium bicarbonate, fertilizer-grade ammonium sulfate
C	Chongqing	Desalination wastewater and by-product salts from the resin industry	Waste brine and dilute brine are concentrated, denitrated and purified before being electrolysed to produce caustic soda and liquid chlorine. Sodium hypochlorite and hydrochloric acid are produced as by-products; some of the products are used in-house, whilst the remainder is sold externally, and the salt sludge is sent for disposal.	Liquid caustic soda, liquid chlorine, high-purity hydrochloric acid, sodium hypochlorite solution

Table S4. Scoring rules for comprehensive benefits of coal chemical waste salt utilization and disposal technology

Indicator category	Evaluation basis	Detailed scoring criteria	Case E1	Case E5	Case E15	Case A	Case B	Case C
1 Policy orientation (A1)	1.1 Industrial structure adjustment guidance catalogue	Encouraged (80~100); Restricted or not listed (60~80); Eliminated (0~60)	#	#	#	#	#	#
	1.2 National policies issued by competent authorities supporting technology promotion	Encouraged (80~100); Generally supported (60~80); Restricted (0~60)	#	#	#	#	#	#
2 Technical advancement (A2)	2.1 Number of major production processes related to waste salt treatment	1 – 5 processes (+10~20); 6~10 (+20~30); ＞10(+30~40)	20	13	20	9	11	8
	2.2 Annual scale of all recovered products	0~5 104t/a (+10~20); 6~10 104t/a (+20~30); ＞10 104t/a (30~40)	0	0	5.1 × 104t/a	4.5 × 104t/a	7 × 104t/a	47.5 × 104t/a
	2.3 Number of recovered product types	0 (+10~20); 1~2 (+20~30); 3~5 (+30~40)	0	0	2	2	2	4
3 Energy consumption (A3)	3.1 Annual electricity consumption	Combined subjective – objective score (+50~100)	3660 × 104 kWh/a	1145 × 104 kWh/a	1116 × 104 kWh/a	1000 × 104 kWh/a	1055 × 104 kWh/a	39400 × 104 kWh/a
	3.2 Annual steam consumption	Combined subjective – objective score (+50~100)	10 × 104t/a	2.15 × 104t/a	45 × 104t/a	1.78 × 104t/a	4.68 × 104t/a	21 × 104t/a
	3.3 Annual natural gas consumption	Combined subjective – objective score (+50~100)	None	None	None	926 × 104t/a	220 × 104t/a	142 × 104t/a
4 Technical applicability (A4)	4.1 Overall strength of investing enterprise	Large (+30~40); Medium (+20~30); Small (+0~20)	Large	Medium	Medium	Small	Small	Medium
	4.2 Suitability considering coal–chemical waste salt characteristics	Highly suitable (+30~40); Generally suitable (+20~30); Unsuitable (+0~20)	*	*	*	*	*	*
	4.3 Consideration of natural environmental conditions	Ecologically fragile area (–10~0); Non–fragile area (+0~10)	Yes	Yes	Yes	No	No	No
	4.4 Operational stability period of the project	<0.5 year (+0~10); 1 – 2 years (+10~20); 3 – 5 years (+20~30)	2 years	4 months	6 years	5 years	3 months	12 months
5 Capital investment (B1)	5 One–time capital investment of the project	Combined subjective – objective score (+50~100)	12.5 billion CNY (approximately USD 1.84 billion)	1.8 billion CNY (approximately USD 0.26 billion)	17 billion CNY (approximately USD 2.50 billion)	5 billion CNY (approximately USD 0.74 billion)	5 billion CNY (approximately USD 0.74 billion)	7.9 billion CNY (approximately USD 1.16 billion)

Table S4. Scoring rules for comprehensive benefits of coal chemical waste salt utilization and disposal technology. (continued)

Indicator category	Evaluation basis	Detailed scoring criteria	Case E1	Case E5	Case E15	Case A	Case B	Case C
6 Operating cost (B2)	6 Costs of water, electricity and chemicals during normal operation	Combined subjective – objective score (+50~100)	5.6 CNY/m3 brine	60 CNY/m3 brine	30 CNY/m3 brine	19 CNY/m3 brine	120 CNY/m3 brine	600 CNY/m3 brine
7 Product profit (B3)	7 Profit of recovered products	Combined subjective – objective score (+50~100)	0	0	150~165 CNY/t	150~300 CNY/t	680~1050 CNY/t	1000~1600 CNY/t
8 Product circulation (B4)	8.1 Trading frequency of products	0~10 times/year (+0~20); 10~20 (+20~40); ＞20（+40~70）	None	None	300 orders/a	1.6 × 104t/a	30 orders/a	2 × 104 orders/a
	8.2 Price fluctuation range	0~500 CNY/t (+0~20); 500~1000 (+10~20); 1000~2000 (+20~30)	1500 (landfill cost)	2500 – 4000 (landfill cost）	NaCl (100~110); Na2SO4 (50~55)	NaCl (50~100); Na2SO4 (100~200)	NaHCO3 (1180~1400); (NH4)2SO4 (700~850)	NaOH(aq) (1100~1400); Cl2(l) (500~800); HCl (250~450); NaClO (350~500)
9 Residual pollution of products (C1)	9 Accumulation of effective components in products	Combined subjective – objective score (+50~100)	Na2SO4 ≤89.63%	Na2SO4 ≤92.37%	NaCl ≥81.4% Na2SO4 ≥98.0%	NaCl ≥97.5% Na2SO4 ≥98%	NaHCO3 ≥98.5%; (NH4)2SO4 ≥ 24.0%	NaOH ≥50% HCl ≥31% NaClO ≥10% Cl2(l) ≥99.6%
10 Annual waste salt treatment capacity (C2)	10 Treated solid waste salt per year under equivalent investment	Combined subjective – objective score (+50~100)	1.98 104t/a/100 million CNY	0.389 104t/a/100 million CNY	0.31 104t/a/100 million CNY	1.20 104t/a/100 million CNY	0.60 104t/a/100 million CNY	0.936 104t/a/100 million CNY
11 Other pollutants generated (C3)	11 Number of secondary pollutants (waste gas, wastewater, solid waste)	0~5 (100~90); 6~10 (90~70); 11~15 (70~40); ＞16 (40~0)	9	8	6	9	15	11
12 Safety risk (D1)	12 Number of hazardous chemicals and potential accident sources	0~5 (100~80); 6~10 (80~70); 11~20 (60~40); ＞20 (0~40)	2	2	2	10	5	13
13 Investment willingness (D2)	13 Enterprise willingness to invest in the technology	Positive (80~100); Neutral (60~80); Negative (0~60)	*	*	*	*	*	*
14 Government acceptance (D3)	14 Satisfaction of local authorities	Satisfied (80~100); Neutral (60~80); Dissatisfied (0~60)	*	*	*	*	*	*
15 Replicability (D4)	15 Difficulty of replicating the project in other regions	Easy (80~100); Moderate (60~80); Difficult (0~60)	*	*	*	*	*	*

Notes: The content marked with "#" in the table indicates that experts scored based on national policy guidelines;"*" indicates scores determined by expert judgment based on project conditions. Indicators A1 and A3 are calculated as the average of sub-scores; A2, A4, and B4 are the sum of sub-scores (values >100 are capped at 100). CNY 1 (approximately USD 0.15).

Table S5. (a) Directly related matrix A

0	13	17	22	21	1 5	14	21	18	19	18	19	20	19	19
18	0	16	18	20	20	16	17	14	20	16	17	19	14	17
19	15	0	14	16	21	17	14	15	17	14	12	18	17	20
18	15	17	0	19	16	17	18	20	17	16	19	19	19	18
20	19	13	15	0	11	16	18	16	19	14	15	18	13	19
18	20	18	13	13	0	18	19	17	15	13	17	19	14	20
20	18	20	18	14	20	0	16	16	15	21	14	18	16	21
18	20	20	17	16	19	19	0	18	19	19	17	18	20	19
18	17	16	19	17	18	15	13	0	13	16	14	18	17	21
19	17	16	13	15	19	20	20	13	0	17	19	19	16	20
16	12	14	20	16	19	19	18	19	19	0	16	20	17	18
18	16	13	19	15	14	16	17	19	18	17	0	19	16	19
17	14	16	17	20	17	18	17	20	15	19	17	0	14	20
17	12	16	19	15	15	14	17	17	15	14	17	17	0	18
19	13	17	17	18	16	18	18	20	18	15	18	17	19	0

Table S5. (b) Comprehensive impact matrix T

0.5157	0.5087	0.4796	0.5322	0.5146	0.5111	0.5360	0.4944	0.4454	0.4942	0.4398	0.4661	0.5818	0.5637	0.5663
0.6389	0.4979	0.5350	0.5991	0.5643	0.5684	0.5970	0.5431	0.5015	0.5460	0.4888	0.5193	0.6294	0.6147	0.6243
0.5726	0.5006	0.4118	0.5250	0.5052	0.5131	0.5348	0.4775	0.4299	0.4843	0.4251	0.4465	0.5684	0.5411	0.5513
0.5723	0.5063	0.4659	0.4648	0.5003	0.5031	0.5290	0.4798	0.4343	0.4900	0.4231	0.4524	0.5720	0.5430	0.5642
0.5655	0.4992	0.4652	0.5215	0.4413	0.5047	0.5368	0.4777	0.4265	0.4829	0.4231	0.4538	0.5739	0.5383	0.5541
0.5631	0.4963	0.4693	0.5214	0.4981	0.4442	0.5388	0.4741	0.4308	0.4836	0.4225	0.4588	0.5645	0.5289	0.5567
0.5554	0.4838	0.4533	0.5158	0.4920	0.5055	0.4573	0.4855	0.4171	0.4758	0.4096	0.4356	0.5621	0.5273	0.5509
0.5458	0.4679	0.4402	0.5028	0.4696	0.4808	0.5112	0.4053	0.4069	0.4622	0.3996	0.4256	0.5480	0.5203	0.5413
0.5926	0.5194	0.4753	0.5403	0.5180	0.5217	0.5421	0.5049	0.3971	0.5032	0.4539	0.4814	0.5791	0.5660	0.5750
0.5433	0.4767	0.4498	0.5089	0.4868	0.4925	0.5113	0.4654	0.4222	0.4139	0.4155	0.4390	0.5495	0.5252	0.5393
0.5822	0.5121	0.4720	0.5341	0.5079	0.5130	0.5414	0.4908	0.4583	0.4983	0.3850	0.4718	0.5652	0.5567	0.5690
0.5592	0.4851	0.4419	0.5085	0.4844	0.4876	0.5071	0.4580	0.4165	0.4618	0.4119	0.3878	0.5455	0.5265	0.5388
0.5758	0.5000	0.4700	0.5273	0.5137	0.5102	0.5300	0.4845	0.4297	0.4864	0.4264	0.4579	0.5026	0.5429	0.5559
0.5763	0.4925	0.4659	0.5150	0.4892	0.4888	0.5059	0.4702	0.4272	0.4769	0.4205	0.4492	0.5575	0.4717	0.5527
0.5954	0.5168	0.4811	0.5477	0.5157	0.5193	0.5417	0.5032	0.4429	0.4987	0.4358	0.4709	0.5873	0.5632	0.5082

Table S5. (c) Dimension normalisation total influence matrix D_N

0.2525	0.2539	0.2266	0.2670
0.2592	0.2482	0.2246	0.2680
0.2588	0.2542	0.2195	0.2676
0.2613	0.2535	0.2251	0.2601

Table S5. (d) Weighted supermatrix W

0.07150	0.07146	0.07144	0.07144	0.06990	0.06991	0.06990	0.06989	0.06204	0.06206	0.06205	0.07353	0.07354	0.07353	0.07354
0.06244	0.06251	0.06245	0.06244	0.06110	0.06110	0.06111	0.06111	0.05423	0.05425	0.05424	0.06429	0.06429	0.06430	0.06429
0.05834	0.05833	0.05840	0.05835	0.05709	0.05708	0.05710	0.05710	0.05069	0.05067	0.05068	0.06008	0.06006	0.06006	0.06007
0.06572	0.06571	0.06572	0.06578	0.06431	0.06431	0.06430	0.06430	0.05708	0.05707	0.05708	0.06765	0.06765	0.06767	0.06765
0.06409	0.06409	0.06409	0.06409	0.06276	0.06271	0.06271	0.06272	0.05567	0.05567	0.05568	0.06597	0.06596	0.06597	0.06598
0.06462	0.06462	0.06461	0.06462	0.06322	0.06328	0.06321	0.06322	0.05613	0.05612	0.05613	0.06651	0.06651	0.06651	0.06652
0.06761	0.06760	0.06760	0.06760	0.06613	0.06612	0.06622	0.06613	0.05873	0.05873	0.05872	0.06959	0.06960	0.06961	0.06960
0.06164	0.06165	0.06166	0.06165	0.06032	0.06033	0.06030	0.06037	0.05354	0.05355	0.05355	0.06347	0.06346	0.06345	0.06345
0.08318	0.08316	0.08319	0.08318	0.08140	0.08139	0.08139	0.08139	0.07233	0.07223	0.07221	0.08563	0.08564	0.08562	0.08563
0.09295	0.09297	0.09294	0.09293	0.09093	0.09093	0.09092	0.09092	0.08072	0.08080	0.08072	0.09568	0.09566	0.09567	0.09567
0.08183	0.08184	0.08184	0.08185	0.08007	0.08008	0.08008	0.08008	0.07105	0.07106	0.07116	0.08424	0.08424	0.08424	0.08425
0.05538	0.05537	0.05539	0.05538	0.05419	0.05418	0.05420	0.05421	0.04809	0.04811	0.04810	0.05706	0.05700	0.05701	0.05701
0.06884	0.06885	0.06883	0.06884	0.06735	0.06737	0.06735	0.06736	0.05981	0.05980	0.05982	0.07088	0.07094	0.07087	0.07087
0.06595	0.06596	0.06596	0.06597	0.06456	0.06457	0.06456	0.06455	0.05730	0.05731	0.05730	0.06791	0.06791	0.06798	0.06791
0.06776	0.06775	0.06775	0.06774	0.06630	0.06629	0.06629	0.06628	0.05886	0.05885	0.05885	0.06975	0.06975	0.06974	0.06981

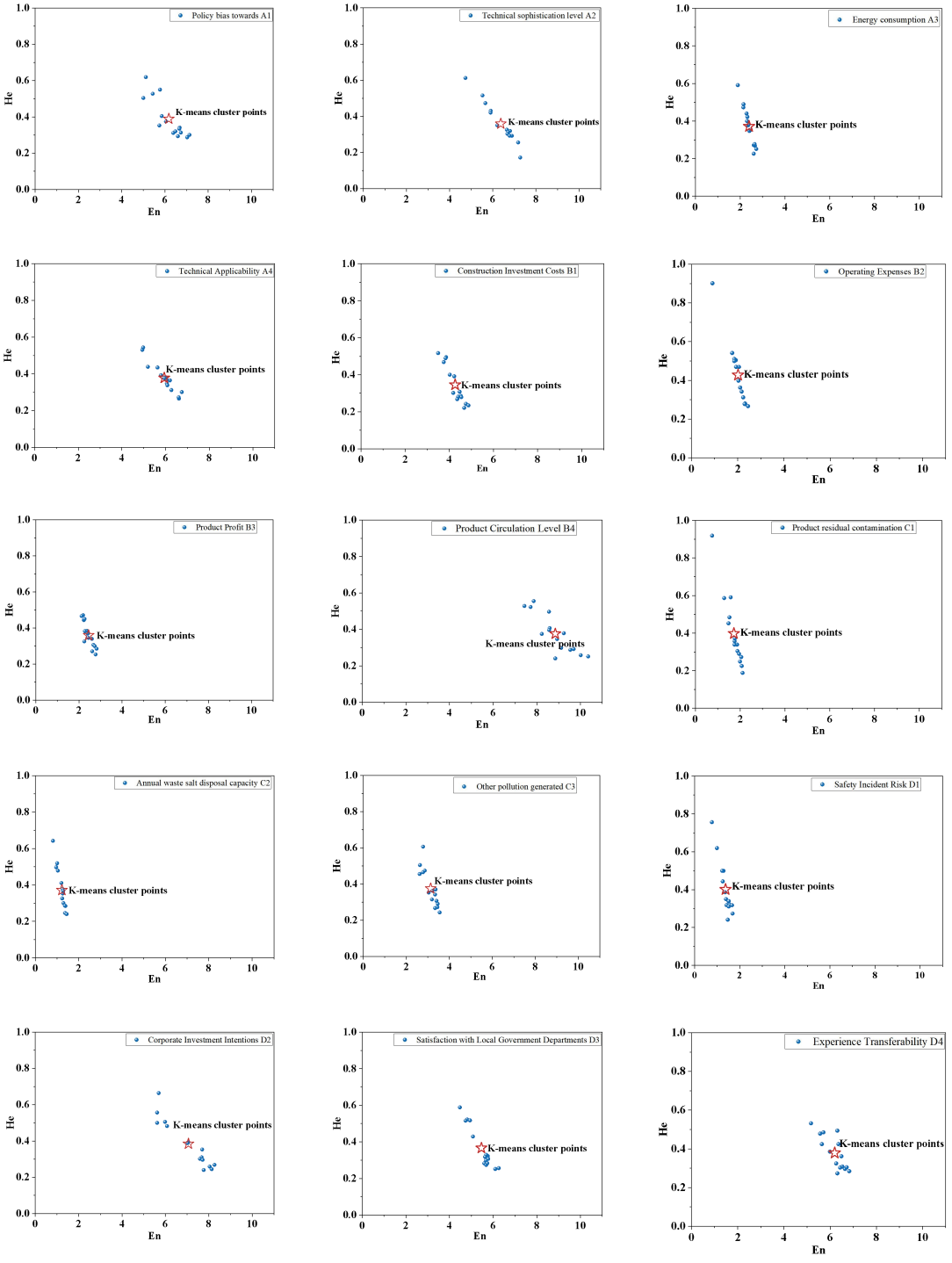

Figure. S1 Sampling scatter clustering relationship of MBCT-SR/K-means algorithm (Enterprise E15)

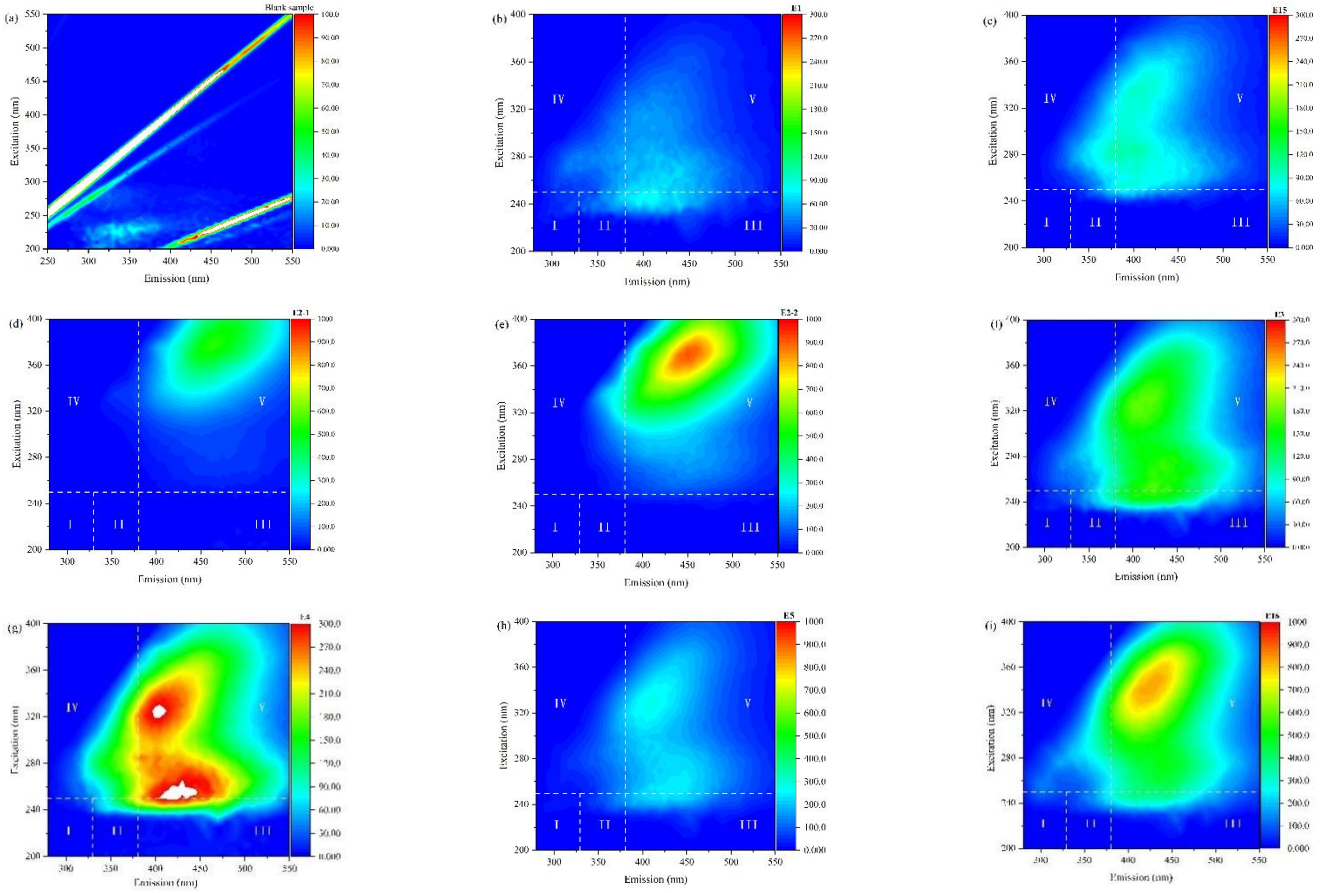

Figure. S2 Three-dimensional fluorescence detection spectra of waste salt from different enterprises. (a) Blank sample, (b) WS1, (c) WS15, (d) WS2-1, (e) WS2-2, (f) WS3, (g) WS4, (h) WS5, (i) WS16. Created by the authors using Origin 2021 software.

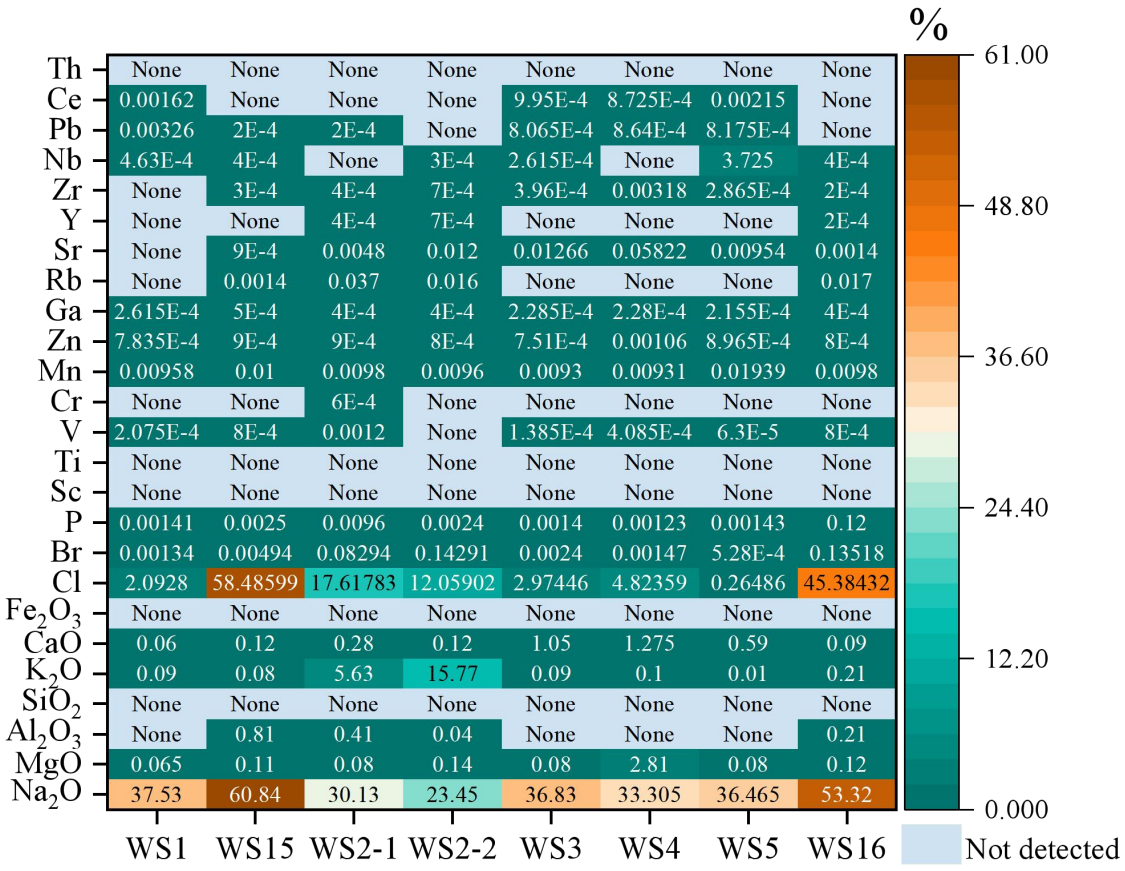

Figure. S3 XRF analysis results of coal chemical waste salt samples

Table S6. Weights of evaluation indicators (based on the DANP method)

Criteria Level	First-level Weight	Rank	Indicator Level	Second-level Weight	Rank
Technical dimension (A)	0.2582	2	Policy preference (A1)	0.0715	3
			Technological advancement (A2)	0.0625	12
			Energy consumption (A3)	0.0584	14
			Technical applicability (A4)	0.0658	9
Economic dimension (B)	0.2526	3	Capital investment cost (B1)	0.0628	11
			Operating cost (B2)	0.0633	10
			Product profitability (B3)	0.0662	8
			Product marketability (B4)	0.0604	13
Environmental dimension (C)	0.2243	4	Residual pollution in products (C1)	0.0723	2
			Annual waste-salt treatment capacity (C2)	0.0808	1
			Additional pollutant generation (C3)	0.0712	4
Social dimension (D)	0.2658	1	Safety accident risk (D1)	0.0571	15
			Corporate investment willingness (D2)	0.0709	5
			Local government satisfaction (D3)	0.0680	7
			Replicability and scalability (D4)	0.0698	6

Table S7. Comprehensive scores of six quantitative indicators

Indicator	E1	E5	E15	A	B	C
A3 (Cost-type)	78.02	83.05	82.82	81.04	81.41	64.35
B1 (Cost-type)	71.00	86.81	67.41	83.52	81.53	79.82
B2 (Cost-type)	82.91	76.08	80.94	84.11	65.12	72.67
B3 (Benefit-type)	60.31	60.00	72.22	74.40	89.46	97.02
C1 (Benefit-type)	65.05	61.99	85.08	86.10	86.20	87.73
C2 (Benefit-type)	76.12	63.16	64.28	73.82	67.98	95.87

Table S8. Standard evaluation set of comprehensive benefits

Evaluation grade	**Very poor**	**Poor**	**Fair**	**Good**	**Very good**
Score interval	[0, 40)	[40, 60)	[60, 80)	[80, 90)	[90, 100]
Expectation Ex_v	20	50	70	85	95
Entropy En_v	6.6667	3.3333	3.3333	1.6667	1.6667
Hyper–entropy He_v	0.1	0.1	0.1	0.1	0.1

Table S9. Dimensions and comprehensive benefit cloud parameters(Ex, En, He) of six technical cases

Case	Technical Dimension A	Economic Dimension B	Environmental Dimension C	Social Dimension D	Comprehensive Benefit
Q1	(67.8, 2.56, 0.370)	(67.8, 0.570, 0.383)	(61.8, 1.24, 0.380)	(68.2, 2.94, 0.382)	(66.7, 2.23, 0.379)
Q6	(64.3, 2.34, 0.386)	(72.5, 0.63, 0.375)	(57.8, 1.26, 0.394)	(71.8, 2.62, 0.386)	(67.1, 2.04, 0.386)
Q2	(82.8, 1.37, 0.375)	(71.9, 0.557, 0.368)	(75.1, 0.758, 0.379)	(86.4, 1.61, 0.378)	(79.7, 1.24, 0.376)
A	(84.6, 0.586, 0.391)	(79.9, 0.373, 0.372)	(81.0, 0.334, 0.383)	(83.3, 1.22, 0.382)	(82.6, 0.803, 0.383)
B	(78.3, 0.674, 0.390)	(77.0, 0.580, 0.372)	(81.0, 0.461, 0.402)	(78.3, 1.47, 0.369)	(78.7, 0.978, 0.382)
C	(81.9, 0.976, 0.383)	(79.6, 0.444, 0.376)	(90.6, 0.510, 0.365)	(77.8, 1.96, 0.372)	(82.0, 1.28, 0.374)