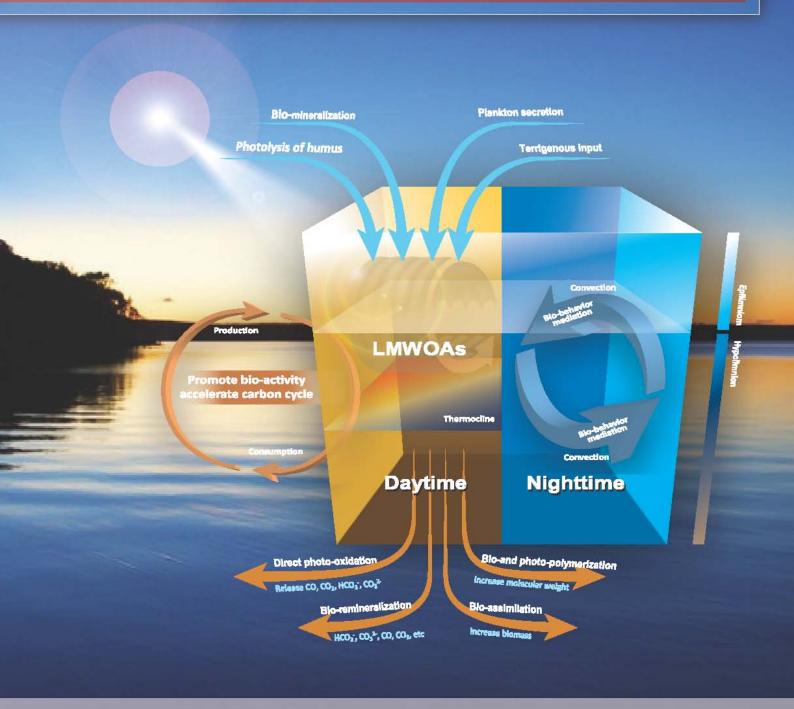
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CONTENTS

Investigation of Inve-molecular weight organic acids and their spatrotemporal variation characteristics in Hongfong Lake, China Min Xian, Freighang Win, Liping Wang, Xinging Li, Rongschang Huang. 224 Investigation of acetylated kapok libers on the sorption of cil in water Jinto Wang, Vin Theng, Asing Wang. Growth characteristics of algae during early stages of phytoplankton bloom in Lake Taihu, China Yilong Jia, Johnson Dan, Min Zhang, Fianktang Kong. 255 Immobilization of airtice oxidizing bacteria using biopolymeric chitosam media Penne Lerisuthisvong, Danagcheewan Boorquak, Wilstornikk Pungrasmi, Sorawit Powtongsook. 266 Preliminary studies on occurrence of monosina antibiotic in Bosque River Watershed Sodarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne Melartand, Forrest Mitchell 268 Aa inovariet integrated system utilizing solar neergy as sower for the teament of decentralized wastewater Changhi Han, Junxin Liu, Hanwen Liang, Xuesong Guo, Liu Li 278 Settling and dewatering characteristics of granulated melanue-oxidizing bacteria Kwang Ho Ahn, Kwang Soo Kim, Sang Won Kang, Chul Yong Um, Won Tae Lee, Kwang Baik Ko 280 Quantification, morphology and source of humic acid, kerogen and black ourbon in ofisbore marine sediments from Xiannen Guif, China Yanting Chen, Jingong Zhan, Lipinar Win, Instance, Glore, Donogita yi Yunta Chen, Jingong Zhan, Lipinar Win, Instance, Ghor, Donogita yi Yunta Chen, Jingong Zhan, Lipinar Win, Instance, Ghor, Donogita yi Yunta Chen, Jingong Zhan, Lipinarchang Sibi, Yanging Song Elefects of ion concentration and natural organic marter on aeneitol'y removal by nanofiltration under different transmenbrane pressures Yang Yu, Changway Zhao, Yangha Changing Song 292 Elefects of ion concentration and natural organic marter on aeneitol'y removal by nanofiltration under different transmenbrane pressures Yang Yu, Changway Zhao, Yangha Chang Song Jing Song Changa Yi, Jinging Ren Characterization of cash byser structure on the microfiltration membrane permeability by iro	Aquatic environment	
Insentinguiation of acetylacet lapok fibers on the sorption of oil in water Jintion Wing, Yian Zheng, Aiqin Wang. Growth characteristics of algue during early stages of phytoplankton bloom in Lake Taihu, China Yuhong Jia, Johnson Dan, Min Zhang, Fanstang Kong. Zhumobilization of intrine exidizing bacteria using biopolymeric chitosan media Peance Lerisuthikwang, Diangchecwan Boonpatak, Wiboonluk Pungrasmi, Sorawit Powtongsook. Pelluliniany studies on occurrence of monestin antibiotic in Bougue River Waterschel Sudarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell An innovative integrated system utilizing solar energy as power for the treatment of decentralized wastewater Changfu Han, Junxin Liu, Hamwen Laing, Xuesong Gloo, Lin Li Settling and dewatering characteristics of granulated methane-oxidizing bateria. Kwang Ho Ahn, Kwang Soo Kim, Sang Won Kang, Chu Yong Uru, Won Tae Lee, Kwang Blak Ko Quantification, morphology and source of humis acid, kerogen and black carbon in offshore marine sediments from Xiamen Gulf, China Yanting Chen, Jinping Zhao, Liquin Yi, Jinsheng Chen, Dongsing Yuan Yang Chen, Jinping Zhao, Liquin Yi, Jinsheng Chen, Dongsing Yuan Yang Chang Chen, Jinping Zhao, Liquin Yi, Jinsheng Chen, Dongsing Yuan Yang Yu, Changwei Zhao, Yangu Wang, Welbong Fian, Zhaokan Luan Xiaotong Zhou, Yangyuan Wu, Hanchang Shi, Yanqing Song Yang Yu, Changwei Zhao, Yangu Wang, Welbong Fian, Zhaokan Luan Characterization of cake Jayer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Siru Pan, Dongsing Lao. Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Jin Wang, Siru Pan, Dongsing Lao. Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Churxiao Chen, Binghui Zheng, Kin Jiang, Zheng Zhao, Yubu Zhao, Fengiao Yi, Jiaying Ren Atmospheric environment Review of heterogeneous photochemical reactions of NOyo on aerosol – A possible daytime source of nitrous acid (H	Investigation of low-molecular weight organic acids and their spatiotemporal variation characteristics in Hongfeng Lake, China	
Jintao Wang, Yian Zheng, Aiqin Wang Growth characteristics of algae during eurly stages of phytoplankton bloom in Lake Taihu, China Yuhong Jia, Johnson Dan, Min Zhang, Fanxiang Kong Immobilization of nitric oxidizing bacteria using biopolymeric chinesan media Prance Letrathiwong, Danaghewan Boonpusk, Wibconils Pungasmi, Sorawit Powrongsook ———————————————————————————————————	Min Xiao, Fengchang Wu, Liying Wang, Xinqing Li, Rongsheng Huang ·····	237
Growth characteristics of algae during early stages of phytoplankton bloom in Lake Taihu, China Yuhong Jia, Johnson Dan, Min Zhang, Fanxing Kong Immobilization of nitrite oxidizing bacteria using biopolymeric chitosan media Prance Lertsuthiswong, Duangeheevan Boonpuak, Wiboonlak Pungrasmi, Sorawit Powtongsook ———————————————————————————————————		
Yuhong, Jin, Johnson Dan, Min Zhang, Fanxining Kong Immubilization of nitrite oxidizing bacteria using biopolymeric chitosam media Prance Lertsuthiwong, Duangcheevan Boonpuak, Whoonluk Pungrasmi, Sorawit Powtongsook 266. Preliminary studies on occurrence of monerasin antibiotic in Bossque River Watershed Sudarshan Kurwaddar, Victoria Sicking, Barry Lambart, Anne Merfardand, Forrest Michell An imnovative integrated system utilizing solar energy as power for the treatment of decentralized wastewater Changful Han, Junxin Liu, Hanwen Liang, Xuesung Guo, Lin Li 276. Settling and dewatering characteristics of granulated methane-oxidizing bacteria Kwang Ho Ahn, Kwang Soo Kim, Sung Won Kang, Chul Yong Um, Won The Lee, Kwang Balak Ko 280. Quantification, morphology and source of humin each, Groego and black activon in offshore marine sediments from Xianen Gulf, China Yaring Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan Evaluation of oxygen transfer parameters of fine-bubble acation system in plug flow acration tank of wastewater treatment plant Xianobong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song Effects of ion concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwed Zhao, Yanqiu Wang, Welmong Pan, Zhaokam Luan Churacterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Sim Pan, Dongping Lao Solar Shadi Shirabution and pollution assessment of mercury in sediments of Luke Taihu, China Churaisa Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren Atmospheric environment Review of heterogenous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Mu, Chang Liu, Hong He Pollutant emission characteristics of rice bask combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso Hylocomium spl	Jintao Wang, Yian Zheng, Aiqin Wang ·····	246
Ismobilization of nitrite oxidizing bacteria using biopolymeric chitosan media Prance Lertsutthiwong, Duangchewan Boonpuak, Wiboonluk Pungrasmi, Sorawit Powtongsook. 26. Preliminary studies on occurrence of monensia antibiotic in Bosque Kiver Walershed Sadarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell Sadarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell Sadarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell Sadarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell Sadarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell Sadarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne Sagary Sadarshan Kurwadkar, Sadarshan Kanasar, Sadarshan Kanasar, Sadarshan Kanas		
Penelmanary studies on occurrence of monensia antibiotic in Bosque Kier Watenhed Sudarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell An innovative integrated system utilizing solar energy as power for the treatment of decentralized wastewater Changfu Han, Junkin Liu, Hammen Linag, Nasong Gno, Liu Li 277. Settling and dewatering characteristics of granulated methane-oxidizing bacteria Kwang Ho Ahn, Kwang Soo Kim, Sung Won Kang, Chul Yong Um, Won Tae Lee, Kwang Baik Ko 288. Quantification, morphology and source of humia exid, keropen and black carbon in offshore marine sediments from Xiamen Gulf, China Yanting Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan 287. Settling and dewatering Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan 288. Setahation of Oxygon transfer parameters of fine-bubble caration system in plug flow acration tank of wastewater treatment plant Xiaohong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song. 289. Effects of ion concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Xangai Wang, Welshong Fan, Zhaokun Luan 300. Characterization of cake layer structure on the microfiltration membrane permeability by iron proc-coagulation Jin Wang, Siru Pan, Dongping Luo Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren 301. Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He 301. Pollutant emission characteristics of fice buss combustion in a votersian fluidized bed incincerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso 302. Pollutant emission characteristics of fice buss combustion in a votersia fluidized bed incincerator Feng Duan, Chiensong Chyang,	Yuhong Jia, Johnson Dan, Min Zhang, Fanxiang Kong ·····	254
Preliminary studies on occurrence of monemsin antibiotic in Bosque River Watershed Sudarsham Kurwadkar, Victoria Sicking, Barry Lumbert, Anne McFarland, Forrest Mitchell An innovative integrated system utilizing solar energy as power for the treatment of decentralized wastewater Changfu Han, Junxin Liu, Hanwen Liang, Xuesong Guo, Lin Li Settling and dewatering characteristics of granulated methane-oxidizing bacteria Kwang Ho Ahn, Kwang Soo Kim, Sung Won Kang, Chul Yong Um, Won Tae Lee, Kwang Baik Ko Quandification, morphology and source of humin eards, kerogen and black carbon in offshore marine sediments from Xiamen Gulf, China Yanting Chen, Inping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan Evaluation of oxygen transfer parameters of fine-bubble aeration system in plug flow aeration tank of wastewater treatment plant Xiaohong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song Effects of fon concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangui Wang, Welhong Fan, Zhaokun Luan Characterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Sin Pan, Dongping Luo- Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zhene, Xia Jiang, Zheng Zhao, Yuzhu Zhao, Fengjiao Yi, Jiaying Ren 31c Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He 20p Dulluan emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso Feng Duan, Chiensong Chyang, Yucheng Chin,		
Sudarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell An innovative integrated system utilizing solar energy as power for the treatment of decentralized wastewater Changfu Han, Junxin Liu, Hamwen Linag, Nacoong Guo, Liu Liu Settling and dewatering characteristics of granulated methane-oxidizing bacteria Kwang Ho Ann, Kwang Soo Kim, Sung Won Kang, Chul Yong Um, Won Tae Lee, Kwang Baik Ko 280 Quantification, morphology and source of humic acid, kerogen and black carbon in offshore marine sediments from Xiamen Gulf, China Yanting Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan 281 Evaluation of oxygen transfer parameters of fine-bubble earation system in plug flow aeration state of wastewater treatment plant Xiaohong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song. Elifects of ion concentration and natural organic matter on arsenict(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangui Wang, Weihong Fan, Zhaokun Luan—300, Tharciterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Siir Pan, Dongning Luo—300 Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren—316 Amospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol — A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He—324 Pollutant emission characteristics of rice busk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso—418 Hillocomium splanders (Hedw) B. S. G. and Pleurocium scheeberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Salishian Dolegowska, Azidraku M. Mignazewski, Artur Michalik BTEX pollution caused by motorcycles in the meagacity of HoChiMinh Tran Th	Pranee Lertsutthiwong, Duangcheewan Boonpuak, Wiboonluk Pungrasmi, Sorawit Powtongsook · · · · · · · · · · · · · · · · · ·	262
An innovaive integrated system utilizing solar energy as power for the treatment of decentralized wastewater Changfu Han, Junxin Liu, Hanwen Liang, Xuesong Guo, Lin Li Settling and dewatering characteristics of granulated methane-oxidizing bacteria Kwang Ho Ahn, Kwang Soo Kim, Sung Won Kang, Chul Yong Um, Won Tae Lee, Kwang Baik Ko 280 Quantification, morphology and source of humic acid, koregon and black earbon in offshore marine sediments from Xiamen Gulf, China Yanting Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan 281 Evaluation of oxygen transfer parameters of fine-bubble aeration system in plug flow aeration tank of wastewater treatment plant Xiaohong Zhao, Vianqiuw Mu, Hanchang Shi, Yanqing Song 292 Elifects of ion concentration and natural organic matter on ansenic (V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangiu Yang, Weihong Fan, Zhaokun Luan Characterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Siru Pam, Dongping Luo Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chansiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren 304 Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol — A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Forg Duan, Chiensong Chyang, Yucheng Chin, Jim Tso Forg Duan, Chiensong Chyang, Yucheng Chin, Jim Tso Hollocomium splendens (Hedw.) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolgowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoe Lan, Phum Anh Minh Environmental biology The Characteristic		
Changfu Han, Junxin Liu, Hanwen Liang, Xuesong Guo, Lin Li Settling and dewatering characteristics of granulated methane-oxidizing bacteria Kwang Ho Ahn, Kwang Soo Kim, Sung Woo Kang, Chul Yong Um, Won Tae Lee, Kwang Baik Ko Quantification, morphology and source of humic acid, kerogen and black carbon in offshore marine sediments from Xiamen Gulf, China Yanting Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan 28: Evaluation of oxygen transfer parameters of fine-bubble acration system in plug flow aeration tank of wastewater treatment plant Xianohong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song Effects of ion concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangui Wang, Welhong Fan, Zhaokun Luan 30: Characterization of cake layer structure on the microlitration membrane permeability by iron pre-coagulation Jin Wang, Sin Pan, Dongping Lu 30: Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren 31: Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxim Ma, Chang Liu, Hong He 32: Pollutant emission characteristics of rice hask combastion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso 43: Psylocomium splendens (Hedw) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabima Dolgowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChilvlinh Tran Thi Ngoc Lan, Pham Anh Minh Environmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Ly, Anzhou Ma, Xuanming Tang, Zhibui Bai, Hongyan Qi, Guoqia	Sudarshan Kurwadkar, Victoria Sicking, Barry Lambert, Anne McFarland, Forrest Mitchell · · · · · · · · · · · · · · · · · ·	268
Settling and dewatering characteristics of granulated methane-oxidizing bacteria Kwang Ho Ahn, Kwang Soo Kim, Sung Won Kang, Chul Yong Um, Won Tae Lee, Kwang Baik Ko————————————————————————————————————		
Kwang Ho Ahn, Kwang Soo Kim, Sung Won Kang, Chul Yong Um, Won The Lee, Kwang Baik Ko. Quantification, morphology and source of humic acid, kerogen and black carbon in offshore marine sediments from Xiamen Gulf, China Yanting Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongsing Yuan 28: Evaluation of oxygen transfer parameters of fine-bubble acration system in plug flow acration tank of wastewater treatment plant Xiaohong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song 29: Effects of ion concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangui Wang, Weihong Fan, Zhaokun Luan Characterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Siru Pan, Dongping Luo Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso 33: Hylocomium splendens (Hedw.) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolggowska, Zdzisław M. Migaszewski, Artur Michalik ETEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Anh Minh Environmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv. Anzhou Ma, Xuanming Tang, Zhibui Bai, Hongyan Qi, Guoqiang Zhuang 36: Effects of nitrogen and phosphorus concentrations on the bioaccumulation of polybrominated diphenyl ethers by Prorocentru		274
Quantification, morphology and source of humic acid, kerogen and black carbon in offshore marine sediments from Xiamen Gulf, China Yanling Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan 28: Evaluation of Oxygen transfer parameters of fine-bubble aeration system in plug flow aeration tank of wastewater treatment plant Xiaohong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song 29: Effects of ion concentration and natural organic matter on arsenic (V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwed Zhao, Yangui Wang, Weithong Fan, Zhaokun Luan 30: Characterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Siru Pan, Dongping Luo 30: Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren 31: Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He 20: Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso 33: Hylocomium splendens (Hedw.) B.S.G. and Pleuroziam schreberi (Brid.) Mitt, as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolegowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Ash Minh 24: Environmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang 35: Tolerance of Chrysamenum maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González Effect		
Yanting Chen, Jinping Zhao, Liqian Yin, Jinsheng Chen, Dongxing Yuan Svabation of oxygen transfer parameters of fine-bubble aeration system in plug flow aeration tank of wastewater treatment plant Xiaohong Zhou, Yuanyuan Wi, Hanchang Shi, Yanqing Song 295 Effects of ion concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangui Wang, Weihong Fan, Zhaokun Luan 306 Characterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Siru Pan, Dongping Luo 307 Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jirzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He 302 Pollutant emission characteristics of rice buse combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso 333 Hylocomium splendens (Hedw.) B. S.G. and Pleuvozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolggowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Ahh Minh 346 Environmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Ly, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang 357 Tolerance of Chrysantenum maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González Effects of nitrogen and phosphorus concentrations on the bioaccumulation of polybrominated diphenyl ethers by Prorocentrum donghaiense Chao Chai,		280
Evaluation of oxygen transfer parameters of fine-bubble aeration system in plug flow aeration tank of wastewater treatment plant Xiaobong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song Effects of ion concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangui Wang, Weihong Fan, Zhaokun Luan 300. Characterization of cale layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Sira Pan, Dongping Luo 300. Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Churkiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren 310. Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He 100. Feng Duan, Chiersong Chyang, Yucheng Chin, Jim Tso 100. Feng Duan, Chiersong Chyang, Yucheng Chin, Jim Tso 100. Holtonenium sphendens (Hedw.) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dobgowska, Zdzisław M. Migaszewski, Artur Michalik 100. 100. 100. 100. 100. 100. 100. 100		
Xiaohong Zhou, Yuanyuan Wu, Hanchang Shi, Yanqing Song Effects of ion concentration and natural organic matter on arsenic (V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhou, Yangui Wang, Weihong Fan, Zhaokun Luan		287
Effects of ion concentration and natural organic matter on arsenic(V) removal by nanofiltration under different transmembrane pressures Yang Yu, Changwei Zhao, Yangui Wang, Weihong Fan, Zhaokun Luan 30. 30. 30. 30. 30. 30. Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren 31. Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jouan, Chiensong Chyang, Yucheng Chin, Jim Tso 32. Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso 33. Hylocomium splendens (Hedw.) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties 3abina Dolegowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChilMinh Tran Thi Ngoc Lan, Pham Anh Minh Tan Thi Ngoc Lan, Pham Anh Minh Tenvironmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang 35. Tolerance of Chrysantemum maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma, del Carmen A. González-Chávez, Rogelio Carrillo-González Chao Chai, Xundong Yin, Wei Ge, Jinye Wang Environmental health and toxicology Umbilical cord blood mercury levels in China Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Mengin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Mengin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Fifect of biomass addition on the surface and adsorption characterization of carbon-based adsorbents from		
Yang Yu, Changwei Zhao, Yangui Wang, Weihong Fan, Zhaokun Luan		295
Characterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation Jin Wang, Siru Pan, Dongping Luo 301 Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren 316 Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He 326 Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso 336 Hylocomium splendens (Hedw.) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolegowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Anh Minh Tran Thi Ngoc Lan, Pham Anh Minh 248 Tenvironmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang 357 Tolerance of Chrysantemum maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma. del Camen A. González-Chávez, Rogelio Carrillo-González Chao Chai, Xundong Yin, Wei Ge, Jinye Wang Cenvironmental health and toxicology Umbilical cord blood mercury levels in China Meiqin Wu, Chonghual Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Menigin Wu, Chonghual Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Menigin Wu, Chonghual Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Menigin Wu, Chonghual Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Menigin Wu, Chonghual Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Menigin Wu, Chonghual Yan, Jian Xu, Wei Wu, Hui Li, Wang, Pengfei Jing Influence of supports on photocatalytic degradation of phenol and 4-chlorophenol in		
Jin Wang, Siru Pan, Dongping Luo Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Journal Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal Chiensong Chyang, Yucheng Chin, Jim Tso Journal May Journal May Migaszewski, Artur Michalik Environmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang Journal May Journal May Journal May May Journal May Jou		302
Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren		
Chunxiao Chen, Binghui Zheng, Xia Jiang, Zheng Zhao, Yuzhu Zhan, Fengjiao Yi, Jiaying Ren		308
Atmospheric environment Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He September Spuan, Chiensong Chyang, Yucheng Chin, Jim Tso Sabina Doltgowska, Zdzisław M. Migaszewski, Artur Michalik Sabina Doltgowska, Zdzisław M. Migaszewski, Artur Michalik Sabina Doltgowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Anh Minh Tran Thi Ngoc Lan, Pham Anh Minh Tran Thi Ngoc Lan, Pham Anh Minh Cenvironmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Ly, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang 357 Tolerance of Chrysantemum maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González Chao Chai, Xundong Yin, Wei Ge, Jinye Wang Chao Chai, Xundong Yin, Wei Ge, Jinye Wang Tenvironmental health and toxicology Umbilical cord blood mercury levels in China Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Revironmental from coal combustion flue gas by modified fly ash Wenqing Xu, Hairui Wang, Tingyu Zhu, Junyan Kuang, Pengfei Jing Influence of supports on photocatalytic degradation of phenol and 4-chlorophenol in aqueous suspensions of titanium dioxide Kashif Naeem, Feng Ouyang Changzi Wu, Min Song, Baosheng Jin, Yimin Wu, Yaji Huang Changzi Wu, Min Song, Baosheng Jin, Yimin Wu, Yaji Huang Changzi Wu, Min Song, Baosheng Jin, Yimin Wu, Yaji Huang Changzi Wa Acated FeyO, nanomaterial: Preparation and application in removal of phosphate from water		
Review of heterogeneous photochemical reactions of NOy on aerosol – A possible daytime source of nitrous acid (HONO) in the atmosphere Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Jinzhu Ma, Yangchem Migaszewski, Artur Michalik Jinzhu Mitta a trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolęgowska, Zdzisław M. Migaszewski, Artur Michalik Jinzhu Migaszewski, Artur Michalik Jinzhu Mitta a trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolęgowska, Zdzisław M. Migaszewski, Artur Michalik Jinzhu Mitta a trace element bioindicators: Statistical comparison of bioaccumulation of polygomental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang Jintha del Carmen A. González-Chávez, Rogelio Carrillo-González Jinzhu Ma, d		316
Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso Bioaccumulative properties Sabina Dolęgowska, Zdzisław M. Migaszewski, Artur Michalik BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Anh Minh Tran Thi Ngoc Lan, Pham Anh Minh Tolic the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang 357 Tolerance of Chrysantemun maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González 616 626 637 638 646 647 648 648 649 649 640 640 640 640 640 640 640 640 640 640	-	
Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso		
Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso	Jinzhu Ma, Yongchun Liu, Chong Han, Qingxin Ma, Chang Liu, Hong He · · · · · · · · · · · · · · · · · ·	326
Hylocomium splendens (Hedw.) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of bioaccumulative properties Sabina Dolegowska, Zdzisław M. Migaszewski, Artur Michalik		
bioaccumulative properties Sabina Dolęgowska, Zdzisław M. Migaszewski, Artur Michalik	Feng Duan, Chiensong Chyang, Yucheng Chin, Jim Tso · · · · · · · · · · · · · · · · · · ·	335
Sabina Dolęgowska, Zdzisław M. Migaszewski, Artur Michalik 346 BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Anh Minh 348 Environmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang 357 Tolerance of Chrysantemum maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González 367 Effects of nitrogen and phosphorus concentrations on the bioaccumulation of polybrominated diphenyl ethers by Prorocentrum donghaiense Chao Chai, Xundong Yin, Wei Ge, Jinye Wang 376 Environmental health and toxicology Umbilical cord blood mercury levels in China Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou 388 Environmental catalysis and materials Mercury removal from coal combustion flue gas by modified fly ash Wenqing Xu, Hairui Wang, Tingyu Zhu, Junyan Kuang, Pengfei Jing 399 Influence of supports on photocatalytic degradation of phenol and 4-chlorophenol in aqueous suspensions of titanium dioxide Kashif Naeem, Feng Ouyang 399 Effect of biomass addition on the surface and adsorption characterization of carbon-based adsorbents from sewage sludge Changzi Wu, Min Song, Baosheng Jin, Yimin Wu, Yaji Huang 409 La-EDTA coated Fe ₃ O ₄ nanomaterial: Preparation and application in removal of phosphate from water	Hylocomium splendens (Hedw.) B.S.G. and Pleurozium schreberi (Brid.) Mitt. as trace element bioindicators: Statistical comparison of	
BTEX pollution caused by motorcycles in the megacity of HoChiMinh Tran Thi Ngoc Lan, Pham Anh Minh		
Tran Thi Ngoc Lan, Pham Anh Minh	Sabina Dołęgowska, Zdzisław M. Migaszewski, Artur Michalik·····	340
Environmental biology Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang		
Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang		348
Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang	Environmental biology	
Tolerance of Chrysantemum maximum to heavy metals: The potential for its use in the revegetation of tailings heaps Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González	Profile of the culturable microbiome capable of producing acyl-homoserine lactone in the tobacco phyllosphere	
Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González	Di Lv, Anzhou Ma, Xuanming Tang, Zhihui Bai, Hongyan Qi, Guoqiang Zhuang ······	357
Effects of nitrogen and phosphorus concentrations on the bioaccumulation of polybrominated diphenyl ethers by <i>Prorocentrum donghaiense</i> Chao Chai, Xundong Yin, Wei Ge, Jinye Wang		
Chao Chai, Xundong Yin, Wei Ge, Jinye Wang	Ma. del Carmen A. González-Chávez, Rogelio Carrillo-González·····	367
Environmental health and toxicology Umbilical cord blood mercury levels in China Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou		
Umbilical cord blood mercury levels in China Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou Environmental catalysis and materials Mercury removal from coal combustion flue gas by modified fly ash Wenqing Xu, Hairui Wang, Tingyu Zhu, Junyan Kuang, Pengfei Jing Influence of supports on photocatalytic degradation of phenol and 4-chlorophenol in aqueous suspensions of titanium dioxide Kashif Naeem, Feng Ouyang Seffect of biomass addition on the surface and adsorption characterization of carbon-based adsorbents from sewage sludge Changzi Wu, Min Song, Baosheng Jin, Yimin Wu, Yaji Huang 405 La-EDTA coated Fe ₃ O ₄ nanomaterial: Preparation and application in removal of phosphate from water	Chao Chai, Xundong Yin, Wei Ge, Jinye Wang ····	376
Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou	Environmental health and toxicology	
Environmental catalysis and materials Mercury removal from coal combustion flue gas by modified fly ash Wenqing Xu, Hairui Wang, Tingyu Zhu, Junyan Kuang, Pengfei Jing	Umbilical cord blood mercury levels in China	
Mercury removal from coal combustion flue gas by modified fly ash Wenqing Xu, Hairui Wang, Tingyu Zhu, Junyan Kuang, Pengfei Jing	Meiqin Wu, Chonghuai Yan, Jian Xu, Wei Wu, Hui Li, Xin Zhou	···· 386
Wenqing Xu, Hairui Wang, Tingyu Zhu, Junyan Kuang, Pengfei Jing	Environmental catalysis and materials	
Wenqing Xu, Hairui Wang, Tingyu Zhu, Junyan Kuang, Pengfei Jing	Mercury removal from coal combustion flue gas by modified fly ash	
Influence of supports on photocatalytic degradation of phenol and 4-chlorophenol in aqueous suspensions of titanium dioxide Kashif Naeem, Feng Ouyang	· · · · · · · · · · · · · · · · · · ·	393
Kashif Naeem, Feng Ouyang		
Effect of biomass addition on the surface and adsorption characterization of carbon-based adsorbents from sewage sludge Changzi Wu, Min Song, Baosheng Jin, Yimin Wu, Yaji Huang		399
Changzi Wu, Min Song, Baosheng Jin, Yimin Wu, Yaji Huang \cdots 405 La-EDTA coated Fe $_3$ O $_4$ nanomaterial: Preparation and application in removal of phosphate from water		
La-EDTA coated Fe ₃ O ₄ nanomaterial: Preparation and application in removal of phosphate from water		405
		413
Serial parameter: CN 11-2629/X*1989*m*184*en*P*24*2013-2		



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Mercury removal from coal combustion flue gas by modified fly ash

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Abstract

Fly ash is a potential alternative to activated carbon for mercury adsorption. The effects of physicochemical properties on the mercury adsorption performance of three fly ash samples were investigated. X-ray fluorescence spectroscopy, X-ray photoelectron spectroscopy, and other methods were used to characterize the samples. Results indicate that mercury adsorption on fly ash is primarily physisorption and chemisorption. High specific surface areas and small pore diameters are beneficial to efficient mercury removal. Incompletely burned carbon is also an important factor for the improvement of mercury removal efficiency, in particular. The C–M bond, which is formed by the reaction of C and Ti, Si and other elements, may improve mercury oxidation. The samples modified with CuBr₂, CuCl₂ and FeCl₃ showed excellent performance for Hg removal, because the chlorine in metal chlorides acts as an oxidant that promotes the conversion of elemental mercury (Hg⁰) into its oxidized form (Hg²⁺). Cu²⁺ and Fe³⁺ can also promote Hg⁰ oxidation as catalysts. HCl and O₂ promote the adsorption of Hg by modified fly ash, whereas SO₂ inhibits the Hg adsorption because of competitive adsorption for active sites. Fly ash samples modified with CuBr₂, CuCl₂ and FeCl₃ are therefore promising materials for controlling mercury emissions

Key words: fly ash; mercury; modified; adsorption; flue gas

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Introduction

Mercury pollution has received considerable attention from environmental researchers due to its high volatility, long persistence, and strong bioaccumulative properties. Given that coal-fired boilers account for a significant fraction of the anthropogenic emissions of mercury into the atmosphere (Pirrone et al., 2010), researchers have actively explored the speciation and control of mercury in coal combustion flue gas. Various technologies for controlling mercury emissions from coal combustion flue gas have been investigated. Such technologies include sorbent injection and catalytic oxidation combined with wet flue gas desulfurization. However, no single technology is applied broadly. Mercury in coal combustion-derived flue gas is present in three forms: elemental mercury (Hg⁰), oxidized mercury (Hg2+), and particulate-bound mercury (Hg_p). Hg²⁺ is water soluble and therefore can be effectively captured by wet flue gas desulfurization systems as a co-benefit. The majority of Hgp can be collected by

electrostatic precipitators or fabric filters. Hg⁰ is the most difficult to remove because of its high volatility and low solubility in water. As a representative adsorbent for Hg⁰, activated carbon is frequently applied using an injection chamber, but does not yield promising results due to its high price (Pavlish et al., 2003). Fly ash has attracted more and more attention because of its lower price (Presto and Granite, 2006).

As indicated in numerous studies, the mercury adsorption properties of fly ash are closely related to the physical properties and chemical composition. The unburned carbon in fly ash plays an important role in adsorption (Wang and Wu, 2006), and the adsorption capacity differences between unburned carbon separated from fly ash and commercial activated carbon are negligible at low mercury concentrations (Wang and Chen, 2004). However, the structure of carbon differs, thus adsorption properties function in different ways (Wang and Chen, 2005). Because the composition and nature of fly ash is highly complex, its adsorption properties toward mercury are the result of the interaction of multiple factors. Nevertheless, the respective

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effects of these factors cannot be distinguished given the numerous species of elements. Adsorption mechanisms remain incompletely understood, giving rise to the need for further studies (Li et al., 2007; Maroto-Valer et al., 2005; López-Antón et al., 2009). Ferric oxides, manganese oxides, copper oxides, and other inorganic compounds enhance Hg adsorption by activated carbon because of their significant catalytic effect on Hg⁰ oxidation (Bhardwaj et al., 2009; Hua et al., 2010; Shen et al., 2010; Lee et al., 2009).

Fly ash is a potential substitute for activated carbon. Inorganic compounds enhance Hg^0 oxidation, thereby improving mercury adsorption. To the best of our knowledge, this study is one of the few that focus on Hg adsorption by modified fly ash. We investigated mercury adsorption by fly ash collected from different plants, and by samples modified with metallic salts. Results show that the fly ash samples modified with $CuBr_2$, $CuCl_2$ and $FeCl_3$ exhibit excellent Hg^0 removal efficiency. On the basis of the characterization results, an adsorption mechanism is proposed.

1 Experimental

1.1 Sample preparation

The fly ash samples were collected from the electrostatic precipitators of different coal-fired plants in Hebei, Hunan, and Inner Mongolia in China, which were labeled as FA-K, FA-X and FA-Y, respectively. Modified fly ash samples were prepared by an impregnation method using the FA-K fly ash and aqueous metallic salt solutions. After impregnation at 25°C for 12 hr, the samples were dried at 110°C for 12 hr. The modified fly ash samples were marked correspondingly as metallic salt-FA, such as CuCl₂-FA, FeCl₃-FA and so on. The metallic salt loading was measured as the weight of metallic salt with respect to the support FA-K, and which was set to 14 wt.% for all the samples.

1.2 Adsorption test

The adsorption reaction was carried out in a fixed-bed quartz flow reactor at atmospheric pressure (Fig. 1). The reactor was a quartz tube (6 mm i.d.) with a thermocouple placed at the external wall of the reactor to control the temperature of the furnace. Fixed amounts of adsorbent mixed with quartz sand were used in all the experiments. The reactor was heated by a temperature-controlled furnace. Feed gases consisting of 6 vol.% O2, 500 ppm SO2, and 20 ppm HCl (when used) in N2 were adjusted by mass flow controllers and introduced into the reactor at a total flow rate of 1 L/min. A constant quantity of 12.58 μg/m³ of Hg⁰ vapor was supplied into the gas steam, with an Hg⁰ permeation tube immersed in a water bath maintained at 40°C. Analysis of Hg⁰ concentrations was monitored in real time with a Lumex RA-915M Zeeman mercury analyzer (Lumex-Marketing JSC, Russia). The

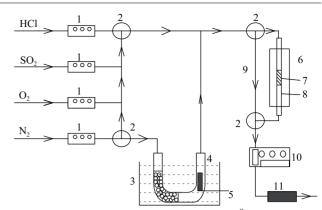


Fig. 1 Flow diagram of the experimental setup for Hg⁰ removal. (1) mass flow controller; (2) three-way valve; (3) water bath; (4) U type pipe; (5) Hg⁰ permeation tube; (6) fixed-bed reactor; (7) catalyst; (8) reaction tube; (9) bypass; (10) Hg analyzer; (11) exhaust gas collector.

 Hg^0 removal efficiency $(\eta, \%)$ was quantified by the following equation:

$$\eta = (1 - \frac{C}{C_0}) \times 100\% \tag{1}$$

where, C and C_0 represent Hg⁰ concentrations at the outlet and inlet of the reactor, respectively.

1.3 Sample characterization

X-ray fluorescence spectroscopy (XRF) was used to conduct composition analysis. XRF measurement was carried out on a LABCENTER XRF-1800 scanning sequence X-ray fluorescence spectrometer (Shimadzu, Japan).

The nitrogen adsorption-desorption isotherms were obtained at -196° C over the whole range of relative pressures, using a Quantachrome NOVA4000 automatic instrument (Quanta Chrome Instrument Co., USA). Specific areas and pore sizes were calculated from these isotherms by the BET and BJH methods, respectively.

X-ray photoelectron spectroscopy (XPS) was carried out on an ESCALab220i-XL spectrometer (Vacuum Generators, UK) using Al $K\alpha$ radiation ($h\nu = 1486.6 \text{ eV}$). Binding energy was corrected using adventitious carbon (284.8 eV).

2 Results and discussion

2.1 Adsorption of Hg⁰ by fly ash samples

The Hg⁰ removal efficiencies of the three fly ash samples were monitored as a function of time on stream at 60°C. As shown in **Fig. 2**, the FA-Y sample initially exhibited 12% Hg⁰ removal efficiency. The efficiency declined to 0% after 50 min. FA-K and FA-X initially showed better activity, with 75% and 68%, respectively. Their removal efficiencies decreased to 30% and 12%, respectively, after 180 min.

The Hg⁰ removal efficiency of FA-K under different adsorption temperatures was also studied, and the results

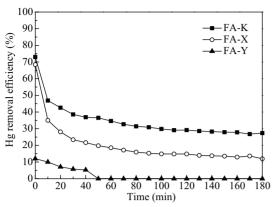


Fig. 2 Hg removal efficiency of fly ash samples (FA-K, FA-X, FA-Y). Reaction conditions: Temp. 60° C; 200 mg sorbents/l g quartz sand; flow rate 1 L/min, N₂ as balance; Hg concentration 12.58 μ /m³. Ash samples (FA-K, FA-X, FA-Y) are referred to Section 1.1.

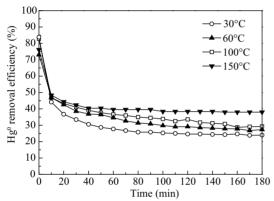


Fig. 3 Effect of temperature on the Hg^0 removal efficiency of FA-K. Reaction conditions: 200 mg sorbents/1 g quartz sand; flow rate 1 L/min; N_2 as balance; Hg concentration 12.58 $\mu g/m^3$.

are shown in **Fig. 3**. Temperature significantly affected the adsorption process. Hg^0 removal efficiency improved as temperature increased, indicating that mercury adsorption by fly ash can be attributed not only to physisorption but also to chemisorption. Because if physisorption occurs alone, removal efficiency decreases with increasing temperature.

2.2 Characterization of the fly ash samples

A composition analysis was conducted to clarify the nature of the different performance variables of the samples. The chemical compositions of the samples are summarized in **Table 1**, which indicates that the fly ash mainly contains incompletely burned carbon, SiO₂, Al₂O₃ and other metallic oxides. The fly ash samples collected from different coal-fired plants also show various concentrations of

 Table 2
 Specific surface areas and average pore diameters of the fly ash samples

Samples	FA-K	FA-X	FA-Y
BET surface areas (m ² /g)	3.96	2.39	0.50
Average pore diameters (nm)	8.42	12.75	39.50

the aforementioned components. The incompletely burned carbon is a core factor in mercury adsorption by fly ash and primarily captures Hg^0 via physical adsorption (Zhao et al., 2010). Given the high carbon content, FA-K showed the best Hg^0 removal efficiency, whereas FA-Y, which had the lowest carbon content, almost failed to remove Hg^0 .

The specific surface areas and average pore diameters of the three samples are summarized in **Table 2**. According to **Table 2**, FA-K has a large specific surface area and minimal average pore diameter. Hg⁰ removal efficiency increased because of this large surface area. In addition, the atomic radius of mercury is 0.152 nm, which is far lower than the samples' average pore diameter. An appropriate aperture is generally favorable for adsorption (Gregg et al., 1989). An excessively large diameter decreases the effective specific surface area and increases the likelihood of desorption reactions. Therefore, FA-K exhibited good performance in mercury adsorption.

The samples were analyzed by XPS to identify the surface characteristics of the active species. The representative photoelectron peaks of C1s in relation to the three samples are depicted in Fig. 4. An essential difference in carbon properties is reflected in the behavior of the C1s lines. That is, the C1s curves of FA-K and FA-X show shoulders at high binding energies of ca. 280.9 and 281.9 eV, respectively. The FA-K and FA-X curves are assigned to the C-M bond, which is formed via the reaction of C and Si, Ti and other elements (Uhlmann et al., 1994; Seal et al., 1998; Selamat et al., 2003). The C-M bond facilitates the catalytic oxidation of Hg⁰ because it can grab electrons, thereby causing an oxidation reaction (Aegerter et al., 1996; Ramanathan and Oyama, 1995). On the basis of the aforementioned results, we conclude that mercury adsorption by fly ash occurs primarily through physisorption, chemisorption and the interaction between the two.

2.3 Mercury adsorption of the fly ash modified with metal chlorides

To improve Hg removal efficiency, the fly ash was modified with a series of metal chlorides and their adsorption performance is depicted in **Fig. 5**. The modified fly ash samples

 Table 1
 Chemical compositions of the fly ash samples

Samples	С	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	TiO ₂	K ₂ O	Others
FA-K (%)	6.85	51.02	32.05	3.04	2.06	1.75	0.84	2.69
FA-X (%)	4.90	44.37	26.68	10.79	3.07	1.86	2.29	5.86
FA-Y (%)	0.62	48.81	24.10	6.17	12.71	0.87	0.82	5.91

showed better Hg removal efficiency than the unmodified samples because the chlorine in metal chlorides acts as an oxidant to promote Hg⁰ oxidation. Granite et al. (2000) proposed that mercury oxidation can occur via a Mars-Maessen mechanism by which adsorbed Hg⁰ reacts with a lattice oxidant such as O* or Cl*. This idea suggests that mercury oxidation can occur via a Mars-Maessen mechanism by which adsorbed or weakly bound Hg⁰ reacts with Cl in chlorides. The reaction mechanism is described as follows:

$$Cl^* + Hg^0(g) \longrightarrow HgCl$$
 (2)

$$HgCl + Cl^* \longrightarrow HgCl_2$$
 (3)

In addition, the metallic element of chlorides also influences the oxidation and adsorption of mercury. The activities of different chlorides follow the order: $CuCl_2 > FeCl_3 > MnCl_2 > CeCl_3 > CoCl_2$. $CuCl_2$ and $FeCl_3$ show better Hg removal efficiency. Cu^{2+} and Fe^{3+} can convert Hg^0 into Hg^{2+} , thereby facilitating the removal of Hg from the flue gas (which has strong oxidative properties). The

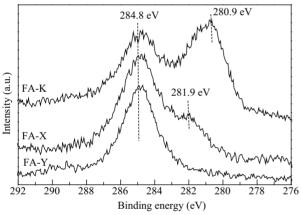


Fig. 4 Experimental C1s XPS spectra of the fly ash samples.

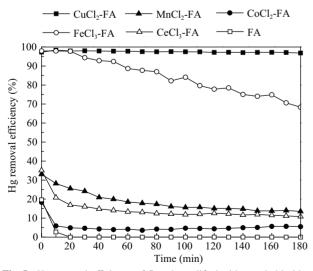


Fig. 5 Hg removal efficiency of fly ash modified with metal chlorides. Reaction conditions: temp. 100°C ; 50 mg sorbents/1 g quartz sand; flow rate 1 L/min; N_2 as balance; Hg concentration $12.58 \, \mu\text{g/m}^3$.

reaction mechanism may be described as follows:

$$CuCl_2 + Hg \longrightarrow HgCl_2 + Cu$$
 (4)

$$2FeCl_3 + Hg \longrightarrow HgCl_2 + 2FeCl_2 \tag{5}$$

2.4 Mercury adsorption of the fly ash modified with copper salt

The fly ash modified with $CuCl_2$ exhibited the best efficiency for mercury removal (**Fig. 5**). Thus the fly ash samples were modified with copper salt to investigate the effect of negative ions on mercury adsorption performance. As shown in **Fig. 6**, negative ions also influence the oxidation and adsorption of mercury. The fly ash modified with $CuBr_2$ showed better Hg removal efficiency than that modified with $CuCl_2$. The activity of different types of copper salt follows the order: $CuBr_2 > CuCl_2 > Cu(NO_3)_2 > CuSO_4$, which is in accordance with the literature (Wu et al., 2012; Sasmaz et al., 2012). Given that the weight ratios of different types of copper salt are the same, the difference in activity is caused primarily by the varying negative ions with different oxidation abilities.

2.5 Effect of reactant gas compositions on the activity of FeCl₃-FA

The fly ash modified with FeCl₃ also exhibited good efficiency for mercury removal (**Fig. 5**). Fe is abundant in fly ash and FeCl₃ is cheaper than CuCl₂. In addition, the Hg⁰ removal efficiency of FeCl₃-FA under N₂ conditions enables the appropriate distinction of the effects of reactant gas on activity. Thus we chose FeCl₃-FA to examine the effect of reactant gas compositions on activity. The activity of FeCl₃-FA for Hg⁰ removal under SO₂ and HCl conditions was examined (**Fig. 7**).

 $\rm O_2$ promotes Hg oxidation and adsorption. In the initial adsorption, Hg removal efficiency reached 100%. After 180 min, Hg removal efficiency remained at 80%, which is higher than that observed under $\rm N_2$ conditions. The promotional effect of $\rm O_2$ is consistent with the literature

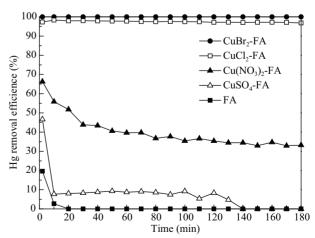


Fig. 6 Hg removal efficiency of fly ash modified with copper salt. Reaction conditions: temp. 100° C; 50 mg sorbents/1 g quartz sand; flow rate 1 L/min; N_2 as balance; Hg concentration $12.58 \,\mu\text{g/m}^3$.

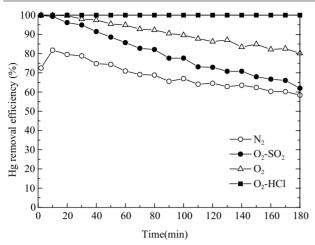


Fig. 7 Hg removal efficiency of modified FeCl₃-FA under different reactant gas compositions. Reaction conditions: Temp. 100°C; 50 mg sorbents/1 g quartz sand; flow rate 1 L/min; $O_2 = 6\%$; HCl 20 ppm; $O_2 = 6\%$; HCl 2

(Granite et al., 2000; Stöhr et al., 1991; Liu et al., 2011; Yan et al., 2011; Guo et al., 2011). A similar mechanism is proposed to explain the promotional effect of O_2 in the current work, where O_2 (ads) is formed through the reaction between an adsorbent and O_2 (g). O_2 (ads) can oxidize Hg^0 to HgO. The reaction may have occurred via the following reactions:

$$O_2(g) \longrightarrow O_2(ads)$$
 (6)

$$Hg^0(g) \longleftrightarrow Hg^0(ads)$$
 (7)

$$O_2(ads) + 2Hg^0(g) \longrightarrow 2HgO(g)$$
 (8)

$$HgO(g) \longleftrightarrow HgO(ads)$$
 (9)

Furthermore, HCl substantially promoted Hg oxidation and adsorption. During the entire 180 min, Hg removal efficiency remained at 100%. As described in Section 2.3, similar to Cl(ads) promotion of Hg oxidation and formation of HgCl₂, HCl was absorbed by FeCl₃-FA and then formed Cl under O_2 conditions. That is, Cl was replenished from gas-phase HCl. The reaction mechanism is described as follows:

$$2HCl + 1/2O_2(ads) \longrightarrow 2Cl^* + H_2O$$
 (10)

$$Cl^* + Hg^0(g) \longrightarrow HgCl$$
 (11)

$$HgCl + Cl^* \longrightarrow HgCl_2$$
 (12)

 $\begin{array}{ccc} \textbf{Table 3} & \textbf{Surface weight percentages of different C compositions on the} \\ \textbf{FeCl}_3 & \textbf{samples before and after reaction in N_2-O_2-SO_2 (as indicated by $C1s$ XPS spectra) \\ \end{array}$

Sample	C-C(H)	C-O	C=O	COO
Before reaction	48.05%	36.29%	6.99%	8.97%
After reaction	78.16%	14.30%	3.38%	4.08%

In addition, SO₂ is present in coal combustion flue gas; thus, the effect of SO₂ under O₂ conditions was also investigated. Unlike O2, SO2 negatively affected Hg removal (Fig. 7) possibly because SO₂ competes with Hg⁰ and O₂ for adsorption active sites. To further explain the negative effect of SO₂ on Hg removal efficiency, we conducted an XPS analysis of FeCl₃-FA samples before and after reaction in N₂-O₂-SO₂. As shown in Fig. 8, the peaks at about 284.8, 286.30, 287.56, and 288.87 eV correspond to C-C(H), C-O, C=O, and COO, whose relative contents are shown in Table 3. C-O, C=O, and COO have oxidative properties, and their contents visibly decreased after reaction. Meanwhile, the content of C-C(H) increased. The peaks at about 198.5 eV correspond to the Cl bond to Fe^{3+} with a net charge of -1, while 200.0 eV corresponds to organic Cl. No significant difference was found between the Cl2p XPS curve of the sample before and after exposure to SO₂. The peak at 169.5 eV is consistent with the S(VI) oxidation state and is assigned to the sulfate species. The reactant gas compositions with SO₂, C–O, C=O, and COO convert Hg⁰ into Hg²⁺ through oxidation, and convert into C-C(H) themselves. On the other hand SO₂ is converted into SO₃ by these oxidations. Therefore, SO₂ competes with Hg⁰ on active sites, thereby negatively affecting Hg oxidation and adsorption.

3 Conclusions

Fly ash shows unique adsorption activity for mercury removal. Incompletely burned carbon is an important factor for improving mercury removal efficiency. In particular, the C–M bond, which is formed via the reaction of C and Ti, Si and other elements, may improve the oxidation of mercury. High specific surface areas and small pore diameters are beneficial for mercury removal efficiency.

Fly ash samples modified with CuBr2, CuCl2 and FeCl3

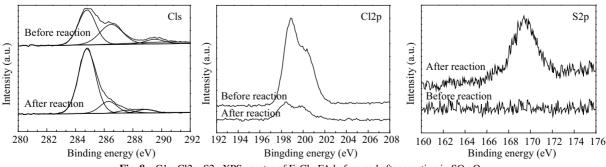


Fig. 8 C1s, Cl2p, S2p XPS spectra of FeCl₃-FA before and after reaction in SO₂-O₂

showed excellent Hg removal efficiency. Mercury oxidation occurs via a Mars-Maessen mechanism, in which adsorbed Hg^0 reacts with a lattice oxidant, such as O^* or Cl^* , on modified fly ash. The presence of O_2 and HCl play a positive role in Hg oxidation and adsorption, whereas SO_2 inhibits Hg removal because of competitive adsorption. Modified fly ash shows promising potential for controlling mercury emissions because of its low cost and high efficiency.

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