**[[1]](#footnote-1)Supplementary material**

Figures:

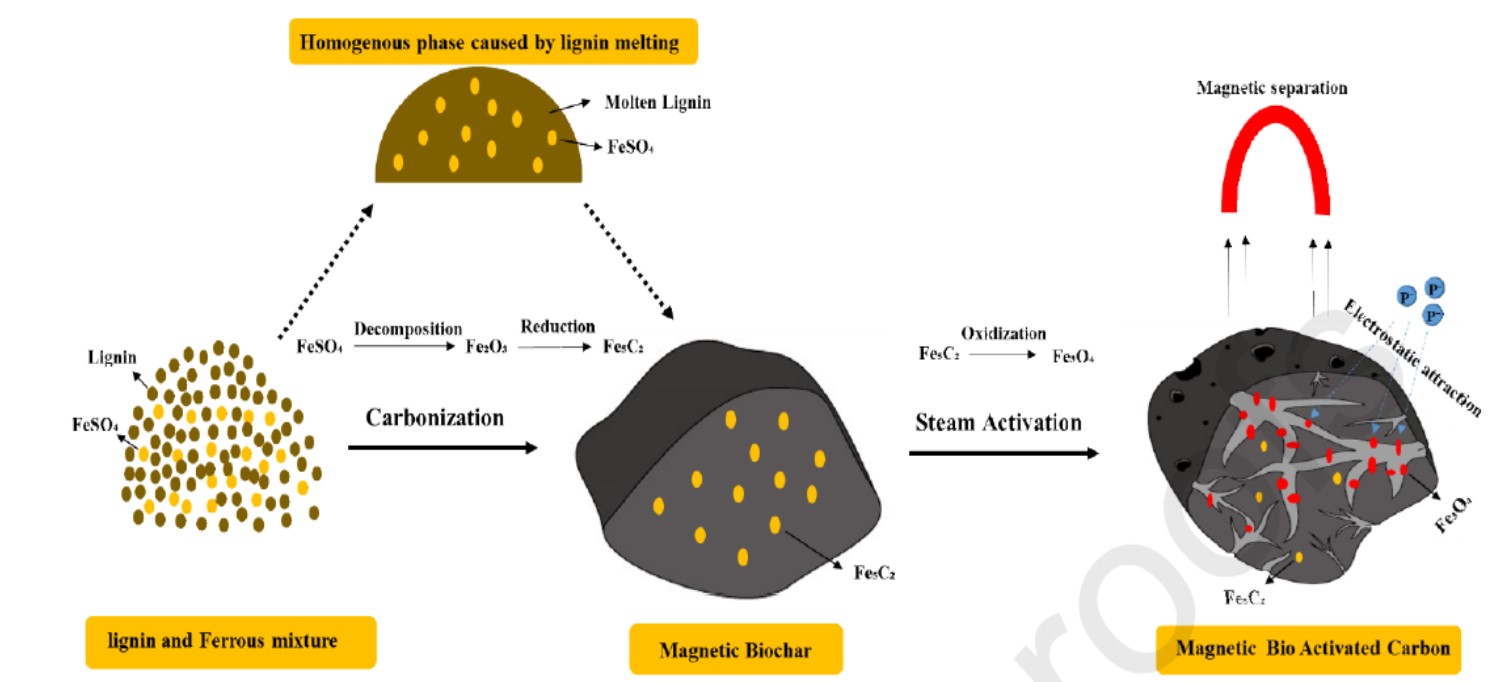


Fig. S1: Preparation of magnetic bio-AC by steam activation and their use for phosphate removal (Han et al. 2020).

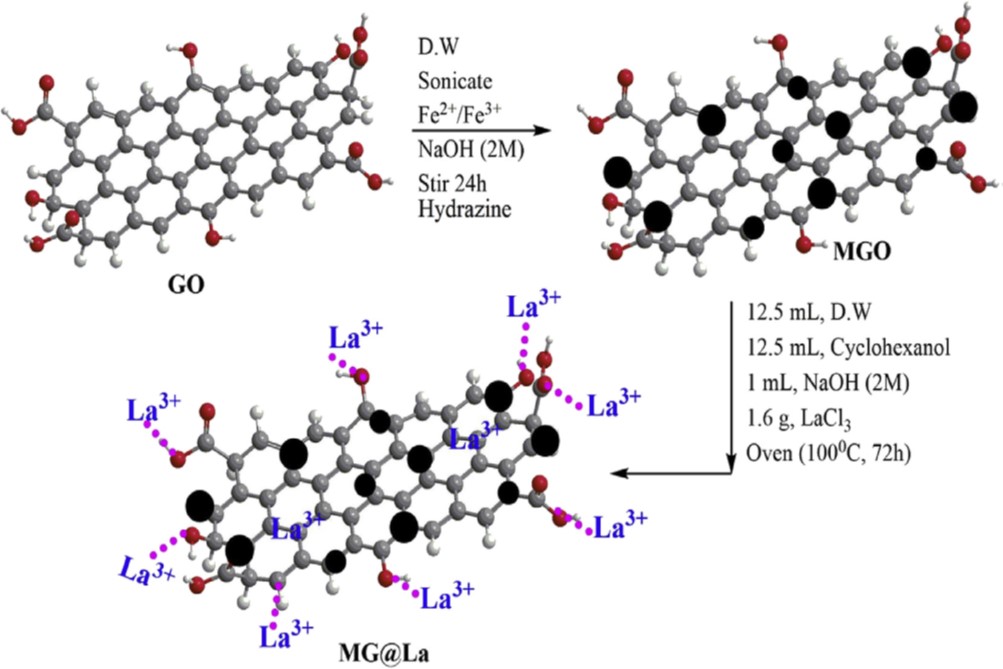


Fig. S2: Schematic presentation of doping lanthanum onto magnetic graphene (Nodeh et al. 2017).

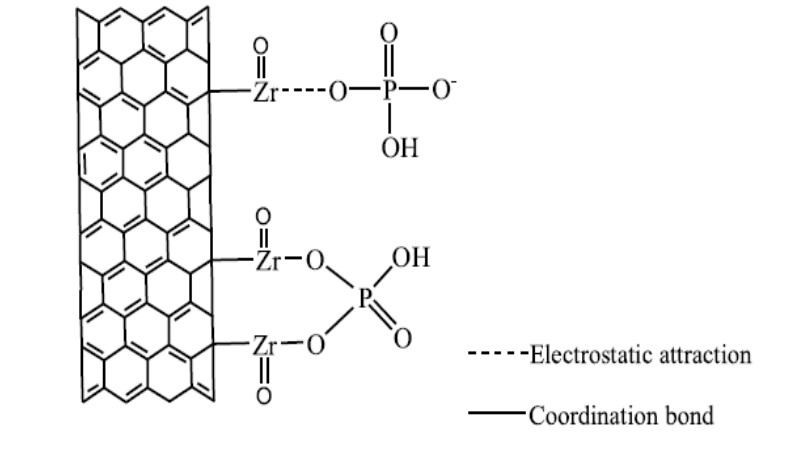


Fig. S3: Adsorption mechanisms of phosphate onto *Zr* modified MWCNTs-COOH (Gu et al. 2019).

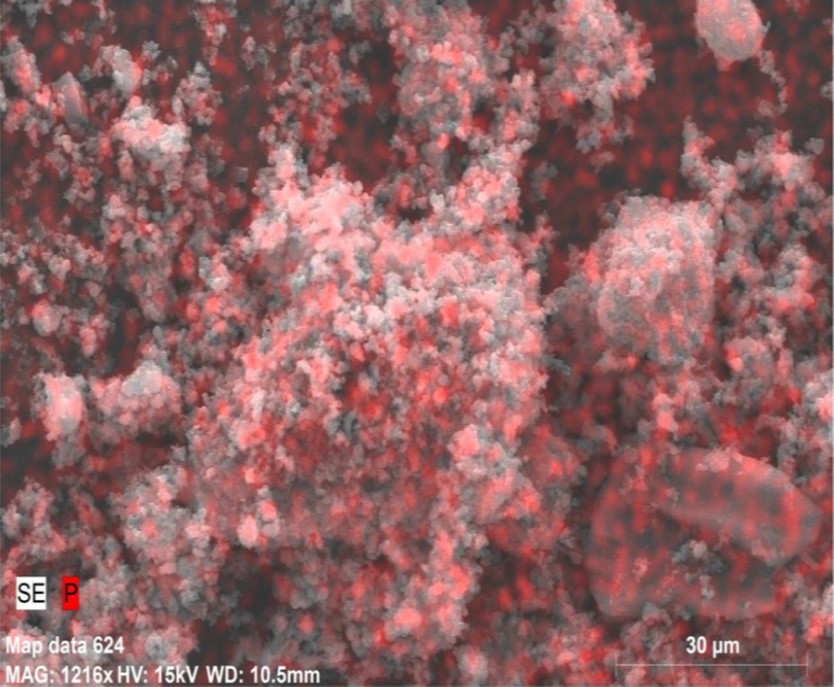


Fig. S4: Phosphorous elemental mapping onto CDC surface after the adsorption process (Almanassra et al. 2020b).

**Tables:**

**Table S1:** Summary of the reported studies of phosphate removal by AC produced by different activation methods

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Adsorbent | Adsorbent preparation technique | Studied phosphate concentration (mg/L) | Surface area (m2/g) | PZC | *Qm* (mg/g) | Kinetics | Isotherm | Adsorbent dose D (g/L),  Optimum pHopt Equilibrium time (T) | Adsorption Mechanism | Ref |
| AC from almond shell | CO2 activation at 1113 K for 30 h. | -  4 – 50 (PO43-) | 968 | - | 4.9 (PO43-) at pH 7, 25 ℃ | - | L | D: 2  pHopt: -  T: - | Electrostatic interactions | (Ferro et al., 1990) |
| AC from olive stone | 1030 | 4.4 (PO43-) at pH 7, 25 ℃ |
| AC from carbon residues of biomass gasification process | Physically modified by CO2 at 800 ℃ for 3 h | 10 – 140 (PO43-) | 590 | - | 30.2 (PO43-) at pH 6, RT | PSO | L | D: 5  pHopt: 6  T: 1440 min | Adsorption is based on the porosity of material | (Kilpimaa et al., 2015) |
| Chemically activated by the wet impregnation method using ZnCl2, then carbonized at 500 ℃ for 1 h | 20 – 125 (PO43-) | 285 | - | 20.5 (PO43-) at pH 8, RT | PSO | L | D: 5  pHopt: 8  T: 1 min | Precipitation | (Kilpimaa et al., 2014) |
| AC from tamarind nut shell (TNSAC) | Impregnation with ZnCl2, then thermal carbonisation at 700 ℃ for 1 – 2 h | - | - | - | 29 at pH 6, 14 ℃ | - | F | D: 0.75 - 8  pHopt: -  T: 100 min | Precipitation  Ion exchange | (Bhargava and Sheldarkar, 1993) |
| AC from coir pith | Chemical activation by ZnCl2, then thermal carbonisation at 700 ℃ | -.  10 – 40 (PO43-) | - | - | 5.1 (PO43-) at pH 4, 35 ℃ | PSO | L, F | D: 6  pHopt: 3 - 10  T: 100 min | Chemisorption, Ion exchange | (Namasivayam and Sangeetha, 2004) |
| AC from coir pith | Chemical activation by H2SO4, then thermal carbonisation at 600 ℃ for 1 h | - | 727.4 | 9.9 | 7.7 (PO43-) at pH 6, 35 ℃ | PSO, Intra-particle diffusion | Timken | D: 4  pHopt: 6 – 10  T: 3 h | Electrostatic interactions, slight chemisorption | (Kumar et al., 2010) |
| AC from Prosopis juliflora | Carbonisation by H2SO4 and thermal treatment at 500 ℃ | 1 – 100 (PO43-) | 358.5 |  | 13.6 (PO43-) at pH 6.7, 30 ℃ | PSO | L | D: 1  pHopt: -  T: 60 min | Chemisorption | (Manjunath and Kumar, 2018) |
| AC from Arundo donax Linn | Impregnation process of feedstock by H4P2O7 then carbonisation at 400 ℃ | 10 – 250 (PO43-) | 1034 | 4.2 | 7.7 (PO43-) at pH 6 | - | L | D: 4  pHopt: 2  T: - | Both physical and chemical adsorption | (Xu et al., 2015) |

**Table S2:** Summary of the reported studies of phosphate removal by modified biomass derived AC

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Adsorbent | Adsorbent preparation technique | Studied phosphate concentration (mg/L) | Surface area (m2/g) | PZC | *Qm* (mg/g) | Kinetics | Isotherm | Adsorbent dose D (g/L),  Optimum pHopt Equilibrium time (T) | Adsorption Mechanism | Ref |
| AC from sewage sludge loaded with 1wt% pyrolusite | Sewage sludge activated by ZnCl2 and H2SO4, then impregnated with pyrolusite and carbonized at 550 ℃ for 1 h | 1 – 50 (P) | 255.63 |  | 10.78 (P) at 25 ℃ | PSO | L | D: 2  pHopt: 6 – 7  T: 30 min | Electrostatic interactions,  Ion exchange | (Yao et al., 2018) |
| Magnetic bio AC from lignin | Activation of lignin and ferric sulphate by steam at 800 ℃ | 5 – 3800 (PO43-) | 369.8 | ˃ 7 | 21.18 (PO43-) at pH 7, 25 ℃ | PSO, PFO | L-F | D: 6.67  pHopt: -  T: 24 h | Electrostatic interactions | (Han et al., 2020) |
| La modified AC from pine cone biomass | Biomass chemically activated with lanthanum chloride at 500 ℃ for 2 h | 10 – 250 (P) | 380.4 | 7.42 | 68.2 (P) at 20 ℃ | PSO | L | D: 1  pHopt: 6 – 7  T: 120 min | - | (Huong et al., 2019) |
| Al/Zn LDH AC from Banana Bract | AC prepared by chemical activation of banana bract using H2SO4 and thermal carbonisation at 400 ℃ for 6 h, metal hydroxides doping by co-precipitation method | - | 90.5 | 6.3 | 87 (PO43-) at 30 ℃ | PSO, Intra-particle diffusion | F | D: 2  pHopt: 6  T: 40 min | Electrostatic attraction, surface complexation, and ion exchange | (Karthikeyan and Meenakshi, 2019) |

**Table S3:** Summary of the reported studies of phosphate removal by activated carbon fibers

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Adsorbent | Adsorbent preparation technique | Studied phosphate concentration (mg/L) | Surface area (m2/g) | PZC | *Qm* (mg/g) | Kinetics | Isotherm | Adsorbent dose D (g/L),  Optimum pHopt Equilibrium time (T) | Adsorption Mechanism | Ref |
| ACF-HFO | Hydrated ferric oxide by sol gel method | 5 – 40 (P) | - | - | 12.9 (P) at RT | PSO | L | D: 1  pHopt: 4  T: 1200 min | Ligand exchange  Electrostatic interactions | (Zhou et al., 2012) |
| ACF | Commercial ACF | 5 – 20 (P) | 1326 | - | 0.6 (P) at 30 ℃ | - | - | D: 2  pHopt: -  T: - | - | (Liu et al., 2011; Zhang et al., 2012b, 2012a) |
| ACF-La | Impregnation method | 1047 | 8.5 | 7.5 (P) at 30 ℃ | PSO, Intra-particle diffusion | L | D: 2  pHopt: 4  T: 360 min | Ion exchange,  Electrostatic interaction,  Lewis acid base interactions |
| ACF-LaOH | Ultrasonic-assisted chemical precipitation. | 10 – 70 (P) | - | 8 | 15.3 (P) at RT | PSO | L | D: 1 – 2.5  pHopt: 2  T: 240 min | Ion exchange,  Electrostatic interaction,  Lewis acid base interactions | (Zhang et al., 2012b) |
| ACF-LaFeOH | Modified form of a proprietary synthetic process developed by  SolmeteX | 5 – 60 (P) | - | 8.5 | 29.4 (P) at RT | PSO | L | D: 1  pHopt: 4  T: 120 min | (Liu et al., 2013) |
| ACF–LaFeO | Impregnation method | - | 734.1 | 9.4 | - | - | - | D: 1  pHopt: 4  T: - | (L. Zhang et al., 2016) |
| ACF-ZrFe | Functionalization for metal oxides | 5 – 60 (PO43-) | - | - | 26.3 (PO43-) at pH 4, 25 ℃ | PSO | L | D: 1  pHopt: 4  T: 6 h | Electrostatic interactions  Ligand exchange | (Xiong et al., 2017) |
| ACF from polyacrylonitrile (PAN) | Activation by K2CO3 at 950 ℃ | 9.6 - 960 (PO43-) | 1277 | - | 64.53 (PO43-) at pH 4.7, 25 ℃ | PSO | L | D: 2  pHopt: -  T: 1 h | - | (Sakamoto et al., 2020) |

**Table S4:** Summary of the reported studies of phosphate removal by granulated activated carbon

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Adsorbent | Adsorbent preparation technique | Studied phosphate concentration (mg/L) | Surface area (m2/g) | PZC | *Qm* (mg/g) | Kinetics | Isotherm | Adsorbent dose D (g/L),  Optimum pHopt Equilibrium time (T) | Adsorption Mechanism | Ref |
| Pre-oxidized GAC loaded with iron oxide | GAC pre-oxidized by KMnO4, then impregnated with iron using ferric chloride | -  250 – 1000 (PO43-) | 1024 | 6.9 | - | PSO | L | D: 20  pHopt: -  T: 300 min | Intra particle diffusion, surface and internal adsorption | (Zach-maor et al., 2011) |
| Pre-oxidized GAC coated with iron | GAC pre-oxidized by KMnO4, then functionalization of iron | 1 – 100 (P) | 794 | - | 10.8 (P) at pH 6.5, 22 ℃ | PSO | L | D: 2  pHopt: -  T: 4 days | Ligand exchange | (Kumar et al., 2017) |
| Pre-oxidized GAC impregnated with ferrihydrite | GAC pre-oxidized by HNO3/H2SO4 followed by iron impregnation | - | 780 | - | 5.73 (P), at pH 6.8, 25 ℃ | PSO | L | D: 3.33  pHopt: -  T: 10 – 12 h | - | (Mahardika et al., 2018) |
| GAC loaded with Fe | Impregnation process | 3 – 60 (PO43-) | 442.2 | 3.5 – 7 | 2.87 (PO43-) at pH 3, 45 ℃ | Internal mass transfer controlling step | (MonoL2SS), two sites Langmuir model | D: 3  pHopt: 3  T: 75 h | Electrostatic interactions  Ligand exchange | (Braun et al., 2019) |
| GAC-La | Hydrolysis of metal salt by NaOH | - | - | - | 14.2 (P) at pH 7.5, 20 ℃ | - | L | D: 2  pHopt: -  T: - | Chemisorption | (Makita et al., 2019) |
| GAC | Commercial GAC | - | 550 | - | 9.35 (PO43-) at pH 7.78, 18 ℃ | PSO, Intra-particle diffusion | L | D: 1  pHopt: 10  T: 30 min | Electrostatic interactions  Ligand exchange  Chemical precipitation | (Ouakouak et al., 2017) |

**Table S5:** Summary of the reported studies of phosphate removal by charcoal based adsorbents

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Adsorbent | Studied phosphate concentration (mg/L) | Carbon content | Surface area  (m2/g) | *Qm* (mg/g) | Kinetics | Isotherm | Adsorbent dose D (g/L),  Optimum pHopt | Adsorption Mechanism | Ref |
| Evacuated coal | 4.75 – 23.7 (PO43-) | 49% | - | 0.11 (PO43-) | - | F | D: 20  pHopt: -  T: 45 min | Precipitation, surface complex formation | (Khan et al., 2013) |
| Activated charcoal | - | - | 1000 | 0.46 (PO43-) at pH 4, 30 ℃ | PSO | L | D: 3.2  pHopt: 4  T: 120 min | Chemisorption | (Mor et al., 2017) |
| Barbecue bamboo charcoal | 5 – 200 (P) | 86.4% | 273.4 | 1.07 (P) at pH 3-4, 25 ℃ | PSO | F | D: 10  pHopt: 5  T: 120 min | Chemisorption | (Yuan et al., 2014) |
| Activated charcoal cloths | - | - | 1300 | ~4.08 (PO43-) at pH 7, 25 ℃ | Intra-particle diffusion | L | D: -  pHopt: 3.5  T: 40 min | Physisorption | (Jayson et al., 1982) |

**Table S6:** Summary of the reported studies of phosphate removal by different carbon structure-based adsorbents

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Adsorbent | Adsorbent preparation technique | Studied phosphate concentration | Surface area (m2/g) | PZC | *Qm* (mg/g) | Kinetics | Isotherm | Adsorbent dose D (g/L),  Optimum pHopt Equilibrium time (T) | Adsorption Mechanism | Ref |
| LaCNFs | Carbonisation of electrospun polyacrylonitrile nanofibers containing La-species. | 1 – 70 ppm (P) | 41.8 | 9.8 | 20.51 (P) at 25 ℃ | PSO | L, F | D: 1  pHopt: 3  T: 250 min | Ligand exchange  Electrostatic forces | (X. Zhang et al., 2016) |
| Cu-Al LDH carbon fibre from Sisal biomass composite | The biomass was decolorized by NaClO2 at 800 C for 4 h followed by calcination at 550 C for 2 h, then one-pot hydrothermal technology for Cu/Al doping | 25 - 1500 ppm (PO43-) | 35.7 | - | 105.26 (PO43-) at pH 8, 15 ℃ | PSO | L | D: 0.8  pHopt: 8  T: 50 min | Anion-exchange, electrostatic attraction and ligand exchange | (Hu et al., 2018) |
| CMK-3 | Carbonisation of SBA-15 and sucrose, zirconium by the wet impregnation method | 0 – 25 ppm (P) | 883.9 | 3.2 | ~ 2 (P) at pH 6.5 and 25 ℃ | - | F | D: 0.25  pHopt: -  T: - | - | (Ju et al., 2016) |
| 29.5%ZrO2@CMK-3 | 598.9 | 4.1 | ~ 20 (P) at pH 6.5 and 25 ℃ | PSO | F | D: 0.25  pHopt: 3.5  T: 660 min | Electrostatic forces at low pH  Surface adsorption mechanism at higher pH |
| CMK-3 | Carbonisation of SBA-15 and sucrose, APTMS by surface functionalization (post-grafting method) | 10 – 90 ppm (P) | 614.2 | 3.9 | 1.99 (P) at pH 7 and 25 ℃ | PSO | F | D: 0.1 – 1  pHopt: -  T: 10 min | - | (Yang et al., 2018) |
| APTMS-CMK-3 | 320.4 | 7.3 | ~ 40 (P) at pH 7 and 25 ℃ | PSO, intra particle diffusion | F | D: 0.1 – 1  pHopt: 4 – 6  T: 150 min for 50 ppm | Electrostatic interactions |
| La-PC | PC by pyrolysis of Sucrose, La doping by impregnation | 3.1 – 62 ppm (PO43-) | 308.9 | - | 13.3 (PO43-) at pH 7.3 and 25 ℃, (24.97 PO43- from sea water) | PSO | L | D: 0.5  pHopt: 3 – 10  T: 1 h | Ligand exchange | (Koilraj and Sasaki, 2017) |
| LPC@La(OH)3 | One‐step carbonisation method to produce LPC from lignin, La doping by facile co-precipitation method | 36.5 – 105 ppm (P) | 473 | - | 60.24 (P) at pH 6 and 25 ℃ | PSO | L | D: 1.2  pHopt: 3  T: 500 min | Ligand exchange  Chemical precipitation | (Liu et al., 2019) |
| Carbide derived carbon | Thermal chlorination of titanium carbide powder at 800 ℃ | 1 – 100 ppm (PO43-) | 1120 | 9.9 | 16.14 (PO43-) at pH 6 and 25 ℃ | PSO | L, Redlich Peterson, Sips | D: 1  pHopt: 4 – 8  T: 6 h | Electrostatic interactions | (Almanassra et al., 2020b) |

1. [↑](#footnote-ref-1)