*Table S1: Proximate and ultimate analysis of the feedstock*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Proximate analysis** | | | | | | | |
| **Feedstock** | **Moisture** | **Volatile matter** | | **Ash** | | **Fixed carbon** | |
| BS | 12.29 | 47.47 | | 26.07 | | 14.16 | |
| CB | 5.530 | 72.60 | | 9.760 | | 12.10 | |
| **Ultimate analysis** | | | | | | | | **Analysis** | |
| **Feedstock** | **C** | **H** | **O** | | **N** | | **S** | **H/C** | **O/C** |
| BS | 33.69 | 6.180 | 29.03 | | 5.030 | | - | 0.1500 | 0.8600 |
| CB | 48.87 | 4.770 | 36.30 | | 0.0500 | | - | 0.0900 | 0.7500 |

*Table S2: Mean metal concentration in BS and CB feedstocks in mg/g*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sample** | **Metal concentration (mg/g)** | | | | | | | | | | | | |
| **Al** | **Ba** | **Co** | **Cr** | **Cu** | **K** | **Mn** | **Ni** | **Pb** | **Sr** | **Zn** | **Fe** |
| **BS** | 0.41 | 0.01 | 0.05 | 0.03 | 0.02 | 0.16 | 0.74 | 0.03 | 0.01 | 0.03 | 0.58 | 46 |
| **SS** (Xingdong Wang, Chi, et al. 2019) | NR | | | ≈ 2 | ≈ 3 | NR | | 0.04 | 0.07 | NR | ≈ 2 | NR |
| **CB** | NR | | | | | | | | | | 0.01 | 0.11 |

\*all with standard deviation (SD) <0.03; NR: not reported

*Table S3: Statistical correlation between parameters and yield*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Statistical correlation for BS** | | | | | | | | | | | | | | | | | | | | | |
|  | | | | | | Actual temp | | | Actual residence time | | | Actual heating rate | | | Particle size | | | Yield | | | |
| Actual temp | | | Pearson Correlation | | | 1 | | | .076 | | | -.104 | | | .147 | | | -.887\*\* | | | |
| Sig. (2-tailed) | | |  | | | .771 | | | .693 | | | .574 | | | .000 | | | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | |
| Actual residence time | | | Pearson Correlation | | | .076 | | | 1 | | | .044 | | | -.062 | | | -.271 | | | |
| Sig. (2-tailed) | | | .771 | | |  | | | .868 | | | .814 | | | .292 | | | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | |
| Actual heating rate | | | Pearson Correlation | | | -.104 | | | .044 | | | 1 | | | .084 | | | -.236 | | | |
| Sig. (2-tailed) | | | .693 | | | .868 | | |  | | | .750 | | | .363 | | | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | |
| Particle size | | | Pearson Correlation | | | .147 | | | -.062 | | | .084 | | | 1 | | | -.313 | | | |
| Sig. (2-tailed) | | | .574 | | | .814 | | | .750 | | |  | | | .222 | | | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | |
| Yield | | | Pearson Correlation | | | -.887\*\* | | | -.271 | | | -.236 | | | -.313 | | | 1 | | | |
| Sig. (2-tailed) | | | .000 | | | .292 | | | .363 | | | .222 | | |  | | | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | |
| \*\*. Correlation is significant at the 0.01 level (2-tailed). | | | | | | | | | | | | | | | | | | | | | | |
| **Statistical correlation for CB** | | | | | | | | | | | | | | | | | | | | | |
|  | | | | | | Actual temp | | | Actual residence time | | | Actual heating rate | | | Particle size | | | Blending ratio | | Yield | |
| Actual temp | | | Pearson Correlation | | | 1 | | | .076 | | | -.104 | | | .147 | | | -.577\* | | -.776\*\* | |
| Sig. (2-tailed) | | |  | | | .771 | | | .693 | | | .574 | | | .015 | | .000 | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | 17 | |
| Actual residence time | | | Pearson Correlation | | | .076 | | | 1 | | | .044 | | | -.062 | | | -.132 | | -.386 | |
| Sig. (2-tailed) | | | .771 | | |  | | | .868 | | | .814 | | | .612 | | .126 | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | 17 | |
| Actual heating rate | | | Pearson Correlation | | | -.104 | | | .044 | | | 1 | | | .084 | | | .179 | | -.338 | |
| Sig. (2-tailed) | | | .693 | | | .868 | | |  | | | .750 | | | .491 | | .185 | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | 17 | |
| Particle size | | | Pearson Correlation | | | .147 | | | -.062 | | | .084 | | | 1 | | | -.254 | | -.369 | |
| Sig. (2-tailed) | | | .574 | | | .814 | | | .750 | | |  | | | .325 | | .145 | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | 17 | |
| Blending ratio | | | Pearson Correlation | | | -.577\* | | | -.132 | | | .179 | | | -.254 | | | 1 | | .540\* | |
| Sig. (2-tailed) | | | .015 | | | .612 | | | .491 | | | .325 | | |  | | .025 | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | 17 | |
| Yield | | | Pearson Correlation | | | -.776\*\* | | | -.386 | | | -.338 | | | -.369 | | | .540\* | | 1 | |
| Sig. (2-tailed) | | | .000 | | | .126 | | | .185 | | | .145 | | | .025 | |  | |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | 17 | |
| \*. Correlation is significant at the 0.05 level (2-tailed). | | | | | | | | | | | | | | | | | | | | | |
| \*\*. Correlation is significant at the 0.01 level (2-tailed). | | | | | | | | | | | | | | | | | | | | | |
| **Statistical correlation for mixed** | | | | | | | | | | | | | | | | | | | | | |
|  | | | | Actual temp | | | Actual residence time | | | Actual heating rate | | | Particle size | | | Blending ratio | | | Yield |
| Actual temp | Pearson Correlation | | | 1 | | | .076 | | | -.104 | | | .147 | | | .577\* | | | -.844\*\* |
| Sig. (2-tailed) | | |  | | | .771 | | | .693 | | | .574 | | | .015 | | | .000 |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 |
| Actual residence time | Pearson Correlation | | | .076 | | | 1 | | | .044 | | | -.062 | | | .132 | | | -.222 |
| Sig. (2-tailed) | | | .771 | | |  | | | .868 | | | .814 | | | .612 | | | .392 |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 |
| Actual heating rate | Pearson Correlation | | | -.104 | | | .044 | | | 1 | | | .084 | | | -.179 | | | -.268 |
| Sig. (2-tailed) | | | .693 | | | .868 | | |  | | | .750 | | | .491 | | | .298 |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 |
| Particle size | Pearson Correlation | | | .147 | | | -.062 | | | .084 | | | 1 | | | .254 | | | -.395 |
| Sig. (2-tailed) | | | .574 | | | .814 | | | .750 | | |  | | | .325 | | | .117 |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 |
| Blending ratio | Pearson Correlation | | | .577 | | | .132 | | | -.179 | | | .254 | | | 1 | | | -.543\* |
| Sig. (2-tailed) | | | .015 | | | .612 | | | .491 | | | .325 | | |  | | | .024 |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 |
| Yield | Pearson Correlation | | | -.844\*\* | | | -.222 | | | -.268 | | | -.395 | | | -.543\* | | | 1 |
| Sig. (2-tailed) | | | .000 | | | .392 | | | .298 | | | .117 | | | .024 | | |  |
| N | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 | | | 17 |
| \*. Correlation is significant at the 0.05 level (2-tailed). | | | | | | | | | | | | | | | | | | | |
| \*\*. Correlation is significant at the 0.01 level (2-tailed). | | | | | | | | | | | | | | | | | | | |

*Table S4: Effect of pyrolysis temperature on mean metal concentration in mg/g*

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sample** | **Al** | **Ba** | **Co** | **Cr** | **Cu** | **K** | **Mn** | **Ni** | **Pb** | **Sr** | **Zn** | **Fe** |
| BS450 | 0.46 | 0.010 | 0.060 | 0.050 | 0.040 | 0.20 | 0.93 | 0.040 | 0.020 | 0.040 | 0.85 | 52 |
| BS550 | 0.50 | 0.020 | 0.11 | 0.070 | 0.040 | 0.25 | 1.2 | 0.050 | 0.020 | 0.060 | 0.77 | 71 |
| BS650 | 0.61 | 0.020 | 0.14 | 0.080 | 0.050 | 0.29 | 1.2 | 0.060 | 0.030 | 0.070 | 0.95 | 71 |
| CB450 | NR | | | | | | 0.010 | NR | | | 0.010 | 0.26 |
| CB550 | NR | | | | | | 0.020 | NR | | | 0.010 | 0.31 |
| CB650 | NR | | | | 0.010 | NR | 0.030 | NR | | | 0.020 | 0.47 |
| Mix450 | NR | | | 0.010 | NR | | 0.080 | NR | | | 0.080 | 3.0 |
| Mix550 | NR | | | 0.010 | NR | | 0.090 | 0.010 | 0.010 | NR | 0.090 | 3.6 |
| Mix650 | NR | | | 0.010 | NR | | 0.090 | 0.010 | 0.010 | NR | 0.090 | 3.9 |

\*all with SD <0.05; NR: not reported

*Table S5: Effect of heating rate, residence time, particle size and blending ratio on mean elemental composition*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Condition** | | **C** | | **H** | | | | **O +ash** | | | **N** | | | | **S** |
| **Heating rate** | | | | | | | | | | | | | | | |
| BS | 3 | 38.06 | | 1.14 | | | | 50.91 | | | 4.02 | | | | 5.86 |
| 5 | 35.26 | | 2.90 | | | | 51.04 | | | 5.35 | | | | 5.45 |
| 8 | 37.71 | | 1.73 | | | | 50.49 | | | 4.71 | | | | 5.36 |
| 10 | 36.01 | | 1.42 | | | | 52.34 | | | 5.88 | | | | 4.35 |
| CB | 3 | 46.03 | | 0.78 | | | | 48.80 | | | 0.39 | | | | 4.01 |
| 5 | 48.96 | | 1.98 | | | | 42.05 | | | 2.05 | | | | 4.96 |
| 8 | 43.82 | | 1.33 | | | | 49.31 | | | 1.26 | | | | 4.28 |
| 10 | 32.46 | | 1.02 | | | | 60.15 | | | 1.60 | | | | 4.77 |
| Mix | 3 | 34.23 | | 1.06 | | | | 55.34 | | | 4.37 | | | | 5.00 |
| 5 | 39.34 | | 1.63 | | | | 49.17 | | | 5.65 | | | | 4.21 |
| 8 | 35.64 | | 1.60 | | | | 53.61 | | | 4.01 | | | | 5.14 |
| 10 | 36.45 | | 1.34 | | | | 51.72 | | | 5.47 | | | | 5.02 |
| **Residence time** | | | | | | | | | | | | | | | |
| BS | 0.5 | 43.87 | 2.90 | | | 41.25 | | | | 5.56 | | | 6.43 | | |
| 1 | 43.15 | 3.07 | | | 41.78 | | | | 5.62 | | | 6.38 | | |
| 2 | 35.26 | 2.90 | | | 51.04 | | | | 5.35 | | | 5.45 | | |
| 3 | 32.52 | 3.08 | | | 52.35 | | | | 5.27 | | | 6.78 | | |
| CB | 0.5 | 49.40 | 1.54 | | | 44.34 | | | | 2.31 | | | 2.41 | | |
| 1 | 49.01 | 1.34 | | | 43.08 | | | | 3.45 | | | 3.12 | | |
| 2 | 48.96 | 1.42 | | | 43.79 | | | | 2.87 | | | 2.96 | | |
| 3 | 48.87 | 1.57 | | | 44.11 | | | | 3.12 | | | 2.33 | | |
| Mix | 0.5 | 45.63 | 2.02 | | | 44.42 | | | | 3.43 | | | 4.50 | | |
| 1 | 44.00 | 1.32 | | | 45.23 | | | | 4.00 | | | 5.45 | | |
| 2 | 39.34 | 1.63 | | | 49.17 | | | | 5.65 | | | 4.21 | | |
| 3 | 35.34 | 1.03 | | | 53.71 | | | | 4.43 | | | 5.49 | | |
| **Particle size** | | | | | | | | | | | | | | | |
| BS | 355- 710 | 34.16 | 1.21 | | | 54.88 | | | | 5.50 | | | 4.25 | | |
| 710- 1000 | 35.37 | 1.57 | | | 52.47 | | | | 5.84 | | | 4.75 | | |
| 1000 - 2000 | 35.26 | 2.90 | | | 51.04 | | | | 5.35 | | | 5.45 | | |
| CB | 355- 710 | 44.68 | 1.68 | | | 48.42 | | | | 2.09 | | | 3.12 | | |
| 710- 1000 | 46.07 | 1.92 | | | 45.20 | | | | 3.27 | | | 3.54 | | |
| 1000 - 2000 | 48.96 | 1.98 | | | 43.05 | | | | 2.05 | | | 3.96 | | |
| Mix | 355- 710 | 32.34 | 1.42 | | | 56.99 | | | | 5.24 | | | 4.02 | | |
| 710- 1000 | 35.34 | 1.51 | | | 53.69 | | | | 5.65 | | | 3.81 | | |
| 1000 - 2000 | 39.34 | 1.63 | | | 49.17 | | | | 5.65 | | | 4.21 | | |
| **Blending ratio (BS: CB)** | | | | | | | | | | | | | | | |
| 0:100 | | | | | 48.96 | | 1.58 | | 45.45 | | | 0.05 | | 3.96 | |
| 75:25 | | | | | 35.34 | | 1.03 | | 52.49 | | | 5.65 | | 5.49 | |
| 50:50 | | | | | 39.34 | | 1.63 | | 49.17 | | | 5.65 | | 4.21 | |
| 25:75 | | | | | 43.46 | | 1.01 | | 45.55 | | | 5.44 | | 4.54 | |
| 100:0 | | | | | 43.87 | | 2.90 | | 39.25 | | | 7.56 | | 6.43 | |

*Table S6: Effect of heating rate and residence time on mean surface area in m2/g*

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample** | **BS** | **CB** | **Mixed** |
| **Heating rate** | |
| 3 | 0.212 | 10.231 | 6.724 |
| 5 | 0.3148 | 9.3376 | 6.145 |
| 8 | 0.6599 | 8.8283 | 5.0752 |
| 10 | 0.5278 | 11.2775 | 55.223 |
| **Residence time** | |
| 0.5 | 0.118 | 8.3018 | 6.0827 |
| 1 | 0.2389 | 8.5781 | 5.8728 |
| 2 | 0.2126 | 9.583 | 6.7113 |
| 3 | 0.3148 | 9.3376 | 6.145 |
| **Particle size** | |
| 355- 710 | 0.3148 | 9.3376 | 6.145 |
| 710- 1000 | 0.264 | 10.23 | 5.245 |
| 1000 – 2000 | 0.247 | 10.235 | 5.882 |
| **Blending ratio (BS: CB)** | |
| 0:100 | 0.3148 |
| 75:25 | 9.3376 |
| 50:50 | 6.145 |
| 25:75 | 1.425 |
| 100:0 | 8.3376 |

|  |
| --- |
| A picture containing plate, indoor, white, half  Description automatically generatedA picture containing plate, chocolate, piece, plant  Description automatically generatedA picture containing indoor, white, close, kitchen appliance  Description automatically generated  *(a) Raw material: BS, CB and mix* |
|
| A picture containing cake, indoor, chocolate, plant  Description automatically generatedA picture containing nature  Description automatically generated**A picture containing cake, chocolate, powder, close  Description automatically generated**  *(b) Raw material: BS, CB and mix* |

*Figure S1: BS, CB and mixed samples (a) before (b) after pyrolysis at 450 °C*

*Table S7. Proximate and ultimate analysis of optimized biochar samples*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Ultimate analysis \*** | | | | | |
| **Sample** | **C** | **H** | **O\*\*** | **N** | **S** |
| Biosolid biochar | 43.87 | 2.90 | 4.07 | 5.16 | 6.43 |
| Cardboard biochar | 51.09 | 2.54 | 28.34 | 0.75 | 2.41 |
| Mixed biochar | 45.63 | 2.02 | 19.85 | 3.43 | 2.01 |
| **Proximate analysis \*\*\*** | | | | | |
| **Sample** | **Moisture** | **Fixed carbon** | **Volatile matter** | **Ash** | |
| Biosolid biochar | 4.82 | 41.86 | 15.75 | 37.57 | |
| Cardboard biochar | 2.29 | 77.35 | 5.49 | 14.87 | |
| Mixed biochar | 6.29 | 44.64 | 22.01 | 27.06 | |

\*dry basis  
\*\*by difference  
\*\*\* air-dried basis