**Supplementary Information**

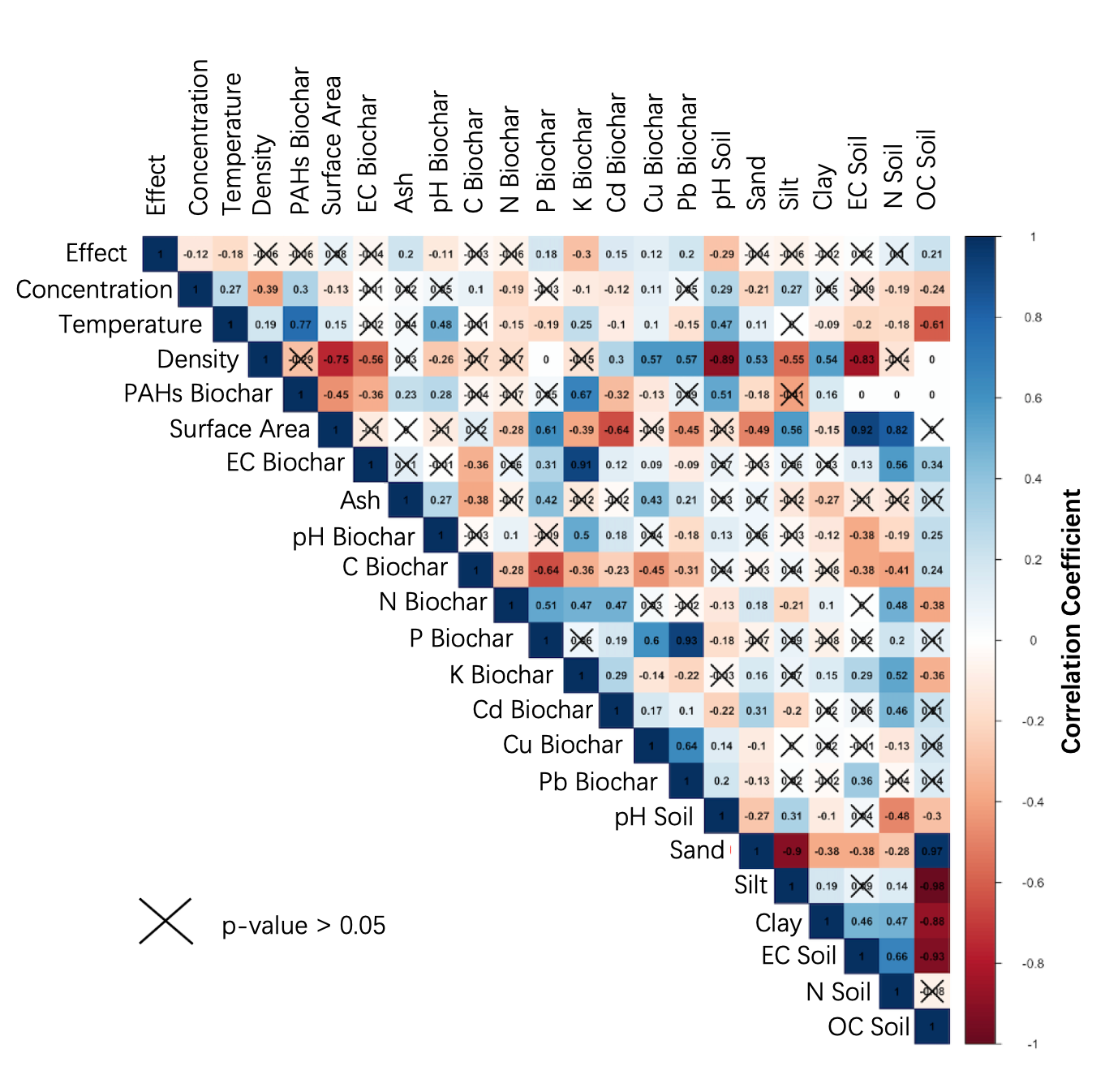
*Table S1. Summary table for meta-analysis conclusion [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20].*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Number of Studies | Impact on Soil productivity | Impact on Soil Microbial Biomass | Impact on Soil Nutrients | Impact on Soil pH | Reference Number |
| 23 | Positive |  |  |  | 11 |
| 371 | Positive | Positive | C: Positive N: Positive P: Positive |  | 14 |
| 103 | Positive | Positive |  | Positive | 8 |
| 111 | Positive |  |  |  | 16 |
| 50 | Neutral | Positive | C: Positive |  | 1 |
| 40 | Positive |  |  | Positive | 4 |
| 136 | Positive |  |  |  | 12 |
| 56 | Positive |  |  | Positive | 17 |
| 17 | Positive |  |  |  | 6 |
| 72 | Hazardous | Positive |  | Positive | 13 |
| 49 | Hazardous | Positive |  |  | 3 |
| 153 | Positive |  | C: Positive |  | 2 |
| 59 | Positive | Positive | C: Positive | Positive | 10 |
| 194 | Neutral | Positive | C: Positive |  | 7 |
| 143 | Positive |  | C: Positive | Positive | 18 |
| 57 | Positive |  |  |  | 9 |
| 62 | Positive |  |  | Positive | 5 |
| 74 | Positive |  |  |  | 19 |
| 242 | Positive |  |  |  | 15 |
| 21 | Positive | Positive |  |  | 20 |

*Table S2 Details about subgroups in meta-analysis*

|  |  |  |
| --- | --- | --- |
| **Grouping** |  | **Number of Data Points** |
| Test Organisms | Animal/Bacteria  Plant | 481 821 |
| pH of biochar | < 6 6-8  ≥ 8 | 76 250 905 |
| Pyrolysis Temperature | < 550 ℃  ≥ 550 ℃ | 710 611 |
| Application rate | < 50 g/Kg  50 g/Kg – 100 g/Kg  ≥ 100 g/Kg | 971 250 176 |
| Biochar Type | Plant Waste Sludge Mix | 923 140 127 139 |
| Endpoint Type | Growth Reproduction Survival | 618 572 139 |
| Soil pH | < 5  5 – 6  ≥ 6 | 88 14 706 |

*Figure S1. Comprehensive relationship between descriptors. Abbreviations: Electrical Conductivity (EC), Organic Carbon (OC),*



*Table S3. Details of descriptors pre-processing for machine learning*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Descriptors | Treatment | Detail | Unit | Missing Value Treatment |
| Endpoint type (growth) | One hot coding | Growth (1), not growth (0) |  |  |
| Endpoint type (survival) | One hot coding | Survival (1), not survival (0) |  |  |
| Endpoint type (reproduction) | One hot coding | Reproduction (1), not reproduction (0) |  |  |
| Tested organisms (animal/bacteria or plant) | One hot coding | Animal/bacteria (1), plant (0) |  |  |
| Biochar type (Plant) | One hot coding | Plant (1), not plant (0) |  |  |
| Biochar type (waste) | One hot coding | Waste (1), not waste (0) |  |  |
| Biochar type (sludge) | One hot coding | Sludge (1), not sludge (0) |  |  |
| Biochar type (mix) | One hot coding | Mix (1), not mix (0) |  |  |
| Application rate | Normalization | Numeric | % (w/w) | Median |
| Pyrolysis temperature | Normalization | Numeric |  | Median |
| Biochar pH | Normalization | Numeric | °C | Median |
| Biochar C content | Normalization | Numeric | % | Median |
| Biochar N content | Normalization | Numeric | mg/Kg | Median |
| Biochar Cd content | Normalization | Numeric | mg/Kg | Median |
| Biochar Cu content | Normalization | Numeric | mg/Kg | Median |
| Biochar Pb content | Normalization | Numeric | mg/Kg | Median |
| Biochar PAHs content | Normalization | Numeric | mg/Kg | Median |
| Biochar electrical conductivity | Normalization | Numeric | S | Median |
| Soil pH | Normalization | Numeric |  | Median |
| Soil texture (sandy) | Normalization | Numeric | % | Median |
| Soil texture (silt) | Normalization | Numeric | % | Median |
| Soil texture (clay) | Normalization | Numeric | % | Median |
| Soil organic content | Normalization | Numeric | % | Median |

*Table S4. Performance of ternary classification model. Bacc here in the model means binary accuracy, which means the accuracy for ternary models to categorize “beneficial” and “hazardous”. For ternary classification model, each category has a sensitivity, means the percentage of correct identification in this category.*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Ternary Classification Models | | SVM linear | SVM Gaussian | NN | RF |
| Testset | Accuracy | 0.51 | 0.58 | 0.61 | 0.64 |
| 95% CI | 0.45 - 0.57 | 0.53 - 0.64 | 0.56 - 0.67 | 0.59 - 0.70 |
| Bacc | 0.66 | 0.75 | 0.79 | 0.80 |
| Sensitivity (Beneficial) | 0.45 | 0.5 | 0.53 | 0.62 |
| Sensitivity (Hazardous) | 0.60 | 0.77 | 0.65 | 0.71 |
| Sensitivity (Neutral) | 0.47 | 0.42 | 0.65 | 0.58 |
| Kappa | 0.26 | 0.36 | 0.42 | 0.46 |
| Training Set | Accuracy | 0.51 | 0.63 | 0.74 | 0.81 |
| 95% CI | 0.48 - 0.55 | 0.60 - 0.66 | 0.71 - 0.77 | 0.78 - 0.83 |
| Bacc | 0.70 | 0.81 | 0.89 | 0.90 |
| Sensitivity (Beneficial) | 0.56 | 0.64 | 0.65 | 0.81 |
| Sensitivity (Hazardous) | 0.6 | 0.78 | 0.81 | 0.87 |
| Sensitivity (Neutral) | 0.36 | 0.41 | 0.71 | 0.70 |
| Kappa | 0.26 | 0.43 | 0.60 | 0.70 |

*Table S5. Exclusion criteria for selecting paper*

|  |
| --- |
| **Exclusion criteria** |
| Research of biochar effects on endpoints other than survival, growth and reproduction |
| Research on materials with name "hydrochar" or "charcoal" without mentioning biochar |
| Research of biochar effect in aquatic environment |
| Research with test conducted in contaminated soil |
| Research without specifying the target species (for example, test about the effect on microbiome community) |
| Research with test conducted with spiked soil (added with fertilizer or amelioments such as compost or sludge) |
| No report of the statistical significance of the findings, making the extraction of the effect impossible |

*Table S6. Details of recorded descriptors in the dataset*

|  |  |
| --- | --- |
| Descriptor Type | Name |
| Biochar Properties (16) | Pyrolysis temperature (℃), Application rate (g/Kg), Ash Content (%), Electronic conductivity (EC, S/cm), Specific surface area (%), Density (Kg/m3), Biochar pH, Carbon content (%), Nitrogen content (%), Phosphorus content (%), Potassium content (%), Cd (mg/Kg), Cu (mg/Kg), Pb (mg/Kg), PAHs content (mg/Kg), biochar type (plant, waste, sludge and mix) |
| Soil Properties (6) | Soil type, Soil texture (percent of sandy, silt, clay), Soil pH, EC (miuS/cm), Nitrogen content (%), organic matter content (%), |
|  |
| Endpoint Type (1) | Name (Growth, Reproduction, Survival) |  |
| Tested Organisms (2) | Name of species, Type of species (Animal/bacteria, Plant) |  |
| Toxicity Test Value (2) | Effect, Standard deviation of Effect |  |

Table S7. Parameter settings of the model in the code

|  |  |
| --- | --- |
| **Name** | **Parameter Settings** |
| Random Forest | After parameters optimization of the model, the parameter set was as follows: ‘ntrees’ = 3000, ‘nodesize’ = 11, ‘mtry’ = 2. |
| Neural Network | Because the dataset has 23 descriptors, the number of nodes in the input layer is 23, and the number of nodes in the hidden layer was set to 12. The number of hidden layers was 1. |
| Supporting Vector Machine | two different SVM models were used for the binary classification of biochar. The first one used a linear SVM, where the parameter ‘Kernel’ of the svm function was set equal to “linear” in the ’e1071’ package, and the second one was a Gaussian SVM, where the parameter ‘Kernel’ parameter was set to “radial”. |

Figure S2. Explanation about sensitivity, specificity, and kappa. Sensitivity: addressing models’ ability of categorizing positive value. Specificity: addressing models’ ability of categorizing positive value. Kappa: compared how model performed to random guessing, usually > 0.4 can be considered performed well.

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