

The Interaction Effect of the Design Parameters on the Water Absorption of the Hemp-Reinforced Biocarbon-Filled Bio-Epoxy Composites

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SUPPLEMENTARY DATA

Table S1: The chemical and proximate analyses of the biomasses, and their biocarbon products at 450 °C, 550 °C, and 650 °C.

| In (%) | H | H450 | H550 | H650 | S | S450 | S550 | S650 |
|-----------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Moisture | 7.26 (±0.03) | 3.17 (±0.01) | 1.56 (±0.11) | 1.59 (±0.09) | 5.47 (±0.09) | 1.19 (±0.10) | 1.28 (±0.20) | 0.25 (±0.26) |
| VM (wet) | 73.34 (±0.97) | 23.30 (±0.34) | 18.94 (±0.57) | 14.86 (±0.26) | 82.71 (±0.48) | 21.52 (±0.02) | 11.71 (±0.67) | 10.17 (±0.24) |
| Ash (dry) | 3.56 (±0.20) | 8.29 (±0.36) | 13.05 (±0.24) | 13.88 (±0.19) | 1.35 (±0.14) | 10.86 (±0.26) | 12.47 (±0.03) | 8.22 (±0.27) |
| FC (dry) | 8.53 | 62.08 | 66.45 | 68.08 | 5.01 | 65.23 | 73.26 | 81.11 |
| N | 0.35 (±0.05) | 0.82 (±0.00) | 0.85 (±0.05) | 0.71 (±0.08) | 1.41 (±0.08) | 1.40 (±0.14) | 1.10 (±0.07) | 0.98 (±0.03) |
| C | 45.34 (±0.25) | 71.06 (±0.26) | 73.88 (±0.52) | 73.54 (±0.21) | 43.35 (±0.27) | 73.20 (±0.02) | 80.54 (±0.25) | 82.03 (±0.39) |
| H | 5.91 (±0.15) | 2.90 (±0.03) | 2.16 (±0.01) | 1.67 (±0.07) | 5.93 (±0.09) | 2.89 (±0.18) | 2.35 (±0.05) | 1.62 (±0.01) |
| S | 0 (±0.00) | 0.03 (±0.04) | 0 (±0.00) | 0.05 (±0.01) | 0.09 (±0.00) | 0 (±0.00) | 0 (±0.00) | 0 (±0.00) |
| O | 47.05 | 14.32 | 10.64 | 15.81 | 45.66 | 14.22 | 2.95 | 1.48 |

FC= Fixed Carbon, VM= Volatile Matter, H=Hemp stalk, S=Switchgrass, H450= Biocarbon from hemp at 450 °C, H550=H Biocarbon from hemp at 550 °C, H650=Biocarbon from hemp at 650 °C, S450 = Biocarbon from switchgrass at 450 °C, S550= Biocarbon from switchgrass at 550 °C, S650= Biocarbon from switchgrass at 650 °C.

Table S2: Showing the average absorption coefficient and their respective water diffusion rate of hemp composite with biocarbon fillers.

| Hemp Biocarbon Composite Samples | Average Absorptivity ($\times 10^{-6}$ (g/m ² . s ^{1/2})) | Average Diffusivity ($\times 10^{-5}$ mm ² /s) | Switchgrass Biocarbon Composite Samples | Average Absorptivity ($\times 10^{-6}$ (g/m ² . s ^{1/2})) | Average Diffusivity ($\times 10^{-5}$ mm ² /s) |
|----------------------------------|---|--|---|---|--|
| H45-50-10 | 1.80 (± 0.244) ^a | 6.74 (± 1.178) ^A | S45-50-10 | 1.72 (± 0.031) ^{abc} | 5.17 (± 0.332) ^{BC} |
| H45-50-20 | 1.04 (± 0.129) ^{bcd} | 2.16 (± 0.369) ^{CD} | S45-50-20 | 0.80 (± 0.162) ^d | 2.14 (± 0.431) ^D |
| H45-100-10 | 1.99 (± 0.054) ^a | 7.69 (± 0.277) ^A | S45-100-10 | 1.74 (± 0.150) ^{abc} | 6.40 (± 0.842) ^{ABC} |
| H45-100-20 | 0.96 (± 0.188) ^{cd} | 2.54 (± 0.897) ^{CD} | S45-100-20 | 1.15 (± 0.084) ^{cd} | 4.35 (± 0.291) ^{BCD} |
| H55-75 | 1.62 (± 0.152) ^{ab} | 6.15 (± 0.841) ^{AB} | S55-75 | 1.28 (± 0.308) ^{bcd} | 3.60 (± 1.011) ^{CD} |
| H65-50-10 | 1.38 (± 0.023) ^{abcd} | 3.46 (± 0.180) ^{BCD} | S65-50-10 | 1.98 (± 0.294) ^a | 7.08 (± 1.661) ^{AB} |
| H65-50-20 | 0.98 (± 0.115) ^{bcd} | 2.55 (± 0.932) ^{BCD} | S65-50-20 | 0.75 (± 0.145) ^d | 1.72 (± 0.493) ^D |
| H65-100-10 | 1.47 (± 0.052) ^{abc} | 5.14 (± 0.533) ^{ABC} | S65-100-10 | 2.00 (± 0.222) ^{ab} | 9.05 (± 0.676) ^A |
| H65-100-20 | 0.72 (± 0.007) ^d | 1.82 (± 0.139) ^D | S65-100-20 | 0.84 (± 0.118) ^d | 2.29 (± 0.157) ^D |

Table S3: Showing the average absorption coefficient and their respective water diffusion rate of composites with and without reinforced hemp fiber and biocarbon filler.

| Samples | Average Absorptivity ($\times 10^{-6}$ (g/m ² . s ^{1/2})) | Average Diffusivity ($\times 10^{-5}$ mm ² /s) | Average Swelling (mm/mm) % |
|---------|---|--|----------------------------|
| HE | 2.41 (± 0.033) | 7.67 (± 0.139) | 12.92 (± 0.251) |
| HaR | 0.17 (± 0.004) | 0.02 (± 0.000) | 0.39 (± 0.023) |

Table S4: Showing the average swelling of the biocomposite samples.

| Sample Code | Pyrolysis Temperature (°C) | Particle Size (μm) | Filler Loading (wt.%) | Hemp Biocarbon Composite Swelling % | Switchgrass Biocarbon Composite Swelling % |
|-------------|----------------------------|--------------------|-----------------------|-------------------------------------|--|
| 45-50-10 | 450 | 50 | 10 | 10.43 (± 0.28) ^{ab} | 10.50 (± 0.50) ^{AB} |
| 45-50-20 | 450 | 50 | 20 | 7.39 (± 0.95) ^{cd} | 7.44 (± 0.32) ^{CD} |
| 45-100-10 | 450 | 100 | 10 | 11.07 (± 0.30) ^a | 11.20 (± 0.13) ^A |
| 45-100-20 | 450 | 100 | 20 | 7.77 (± 0.48) ^{bcd} | 9.01 (± 0.42) ^{BC} |
| 55-75 | 550 | 75 | 15 | 9.84 (± 0.28) ^{abc} | 7.53 (± 0.71) ^{CD} |
| 65-50-10 | 650 | 50 | 10 | 8.35 (± 0.12) ^{bcd} | 9.92 (± 0.62) ^{AB} |
| 65-50-20 | 650 | 50 | 20 | 7.35 (± 0.29) ^{cd} | 5.56 (± 0.46) ^E |
| 65-100-10 | 650 | 100 | 10 | 8.46 (± 1.61) ^{abcd} | 10.67 (± 0.47) ^{AB} |
| 65-100-20 | 650 | 100 | 20 | 6.23 (± 0.25) ^d | 6.94 (± 0.17) ^{DE} |

Table S5: Showing the average flexural modulus (MPa) of the hemp-composites before and after the water absorption.

| Sample Code | Pyrolysis Temperature (°C) | Particle Size (µm) | Filler Loading (wt.%) | Flexural Modulus (MPa) | | | |
|-------------|----------------------------|--------------------|-----------------------|------------------------|--------------------|-----------------------|--------------------|
| | | | | Hemp Biocarbon | | Switchgrass Biocarbon | |
| | | | | Before | After | Before | After |
| 45-50-10 | 450 | 50 | 10 | 68.90 (±6.57) | 37.85 (±0.535) | 76.63 (±0.73) | 43.80 (±1.703) |
| 45-50-20 | 450 | 50 | 10 | 81.65 (±8.72) | 40.38 (±8.986) | 120.59 (±35.72) | 56.72 (±2.031) |
| 45-100-10 | 450 | 100 | 10 | 61.02 (±2.43) | 39.81 (±2.245) | 72.01 (±5.43) | 36.69 (±2.936) |
| 45-100-20 | 450 | 100 | 20 | 95.83 (±18.44) | 66.96 (±15.858) | 119.79 (±21.03) | 59.33 (±3.735) |
| 55-75 | 550 | 75 | 15 | 92.51 (±4.13) | 35.04 (±2.224) | 100.18 (±5.83) | 59.44 (±23.648) |
| 65-50-10 | 650 | 50 | 10 | 70.57 (±2.51) | 33.95 (±2.974) | 63.22 (±10.35) | 43.05 (±3.330) |
| 65-50-20 | 650 | 50 | 20 | 89.52 (±3.56) | 59.57 (±0.305) | 145.37 (±6.40) | 74.76 (±6.132) |
| 65-100-10 | 650 | 100 | 10 | 87.85 (±4.72) | 58.69 (±8.085) | 101.70 (±8.55) | 47.86 (±7.641) |
| 65-100-20 | 650 | 100 | 20 | 137.25 (±10.23) | 97.29 (±14.011) | 141.92 (±19.35) | 88.40 (±25.570) |

Table S6: Showing the average energy at break of the hemp-composites before and after the water absorption.

| Sample Code | Pyrolysis Temperature (°C) | Particle Size (µm) | Filler Loading (wt.%) | Hemp Biocarbon Composites Energy at Break (J/m ²) | | Switchgrass Biocarbon Composites Energy at Break (J/m ²) | |
|-------------|----------------------------|--------------------|-----------------------|---|-----------------|--|--------------------|
| | | | | Before | After | Before | After |
| 45-50-10 | 450 | 50 | 10 | 87.86 (±4.51) | 201.09 (±44.78) | 83.03 (±19.72) | 212.45 (±9.40) |
| 45-50-20 | 450 | 50 | 20 | 61.39 (±6.84) | 176.70 (±3.82) | 67.79 (±7.88) | 143.65 (±27.36) |
| 45-100-10 | 450 | 100 | 10 | 113.12 (±7.36) | 263.20 (±49.20) | 124.94 (±19.89) | 236.66 (±8.16) |
| 45-100-20 | 450 | 100 | 20 | 73.93 (±4.64) | 165.06 (±30.70) | 78.67 (±16.62) | 148.85 (±17.43) |
| 55-75 | 550 | 75 | 15 | 107.06 (±18.98) | 206.68 (±41.29) | 96.39 (±22.67) | 168.11 (±11.83) |
| 65-50-10 | 650 | 50 | 10 | 80.03 (±4.83) | 206.38 (±35.84) | 65.46 (±10.27) | 219.22 (±5.15) |
| 65-50-20 | 650 | 50 | 20 | 72.14 (±3.71) | 172.98 (±9.04) | 80.94 (±7.35) | 149.29 (±46.88) |
| 65-100-10 | 650 | 100 | 10 | 124.80 (±17.29) | 201.93 (±39.48) | 83.74 (±2.75) | 184.42 (±3.95) |
| 65-100-20 | 650 | 100 | 20 | 78.31 (±26.75) | 168.44 (±12.33) | 70.11 (±26.75) | 179.56 (±14.00) |

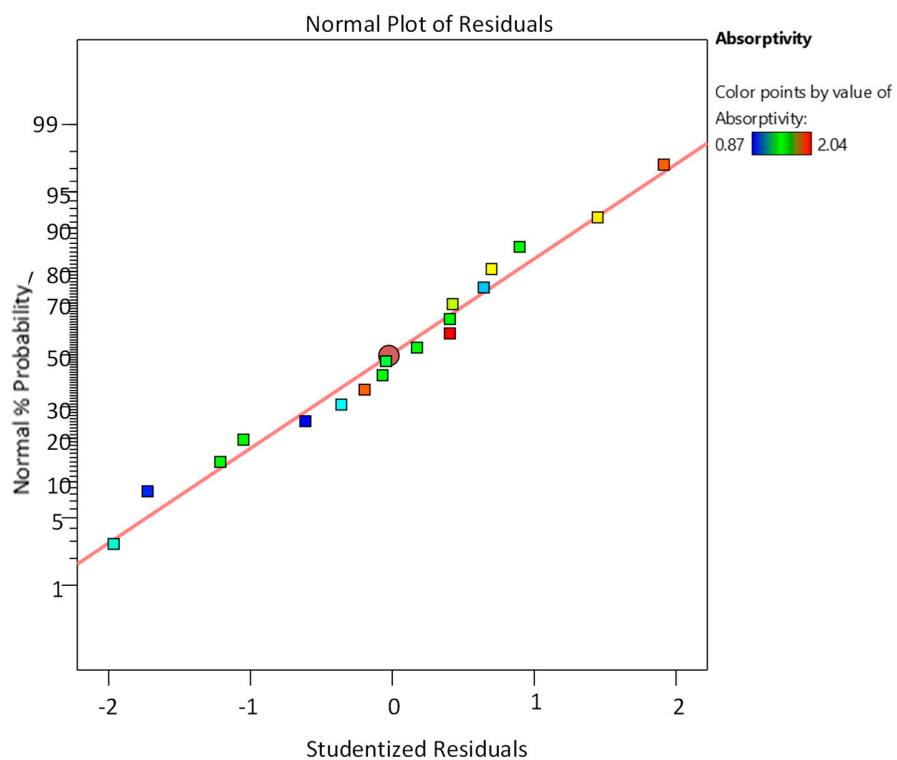


Figure S1: Normal probability plot of Studentized residuals of the hemp biocarbon composite's water absorptivity.

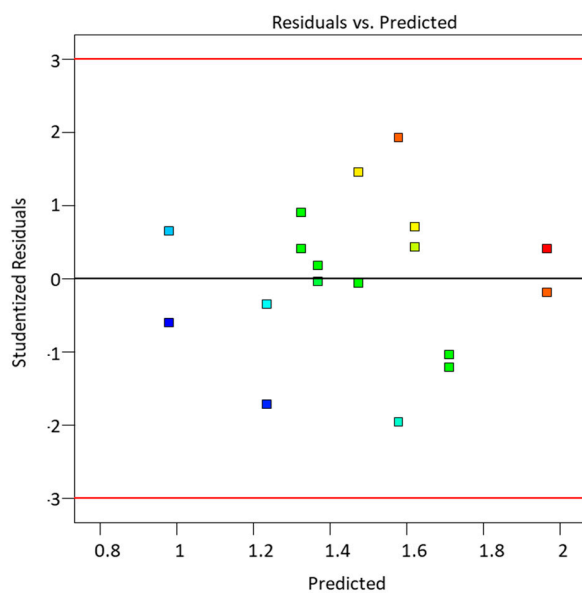


Figure S2: Residuals vs. predicted values of Studentized residuals of the hemp biocarbon composite's water absorptivity.

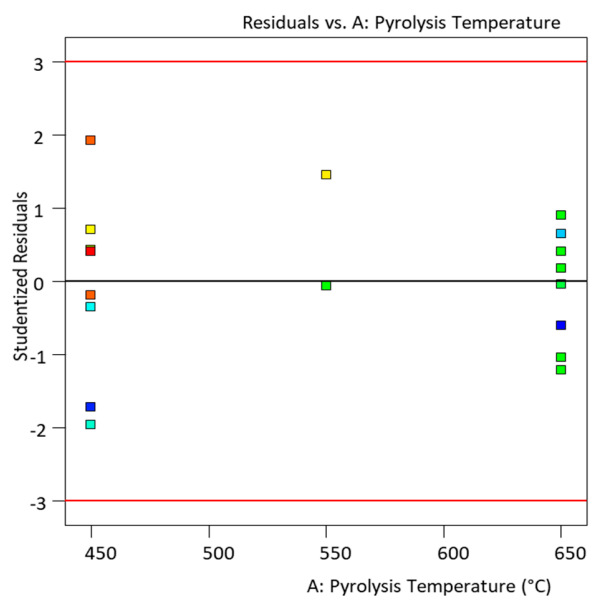


Figure S3: Residuals vs. pyrolysis temperature of Studentized residuals of the hemp biocarbon composite's water absorptivity.

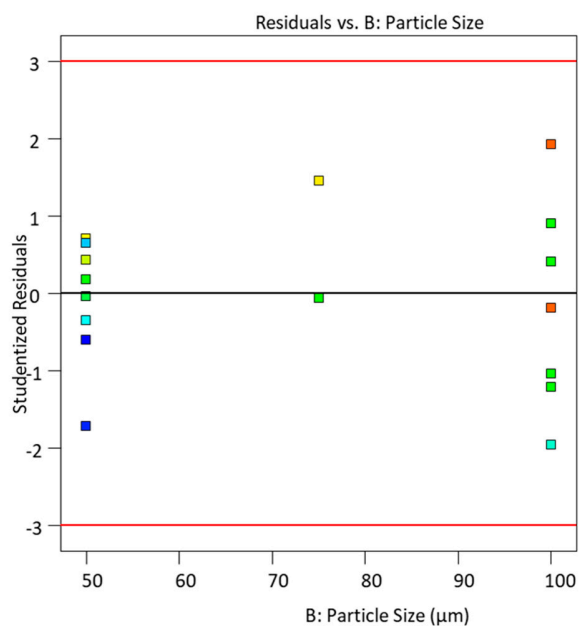


Figure S4: Residuals vs. particle size of Studentized residuals of the hemp biocarbon composite's water absorptivity.

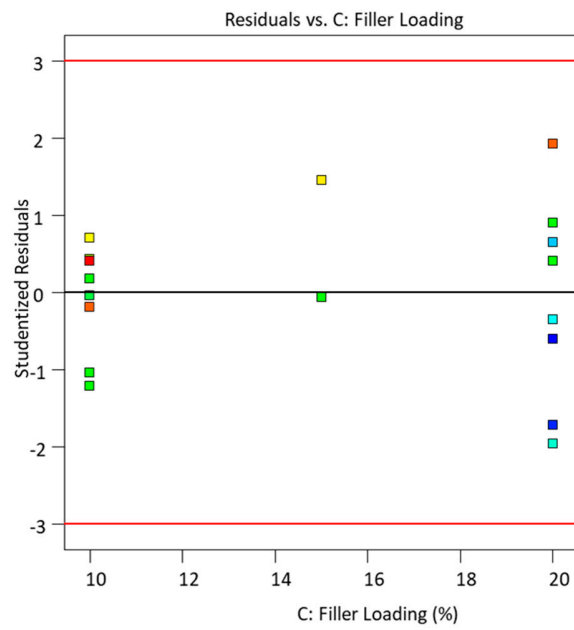


Figure S5: Residuals vs. filler loading values of Studentized residuals of the hemp biocarbon composite's water absorptivity.

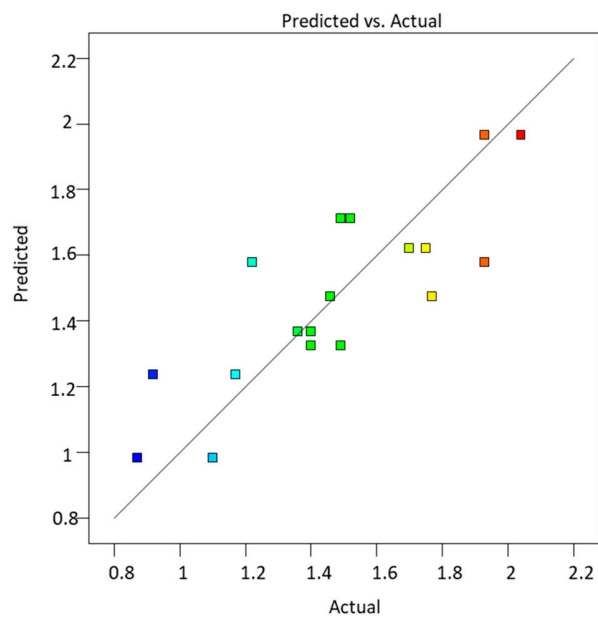


Figure S6: Predicted vs. actual data of the hemp biocarbon composite's water absorptivity.

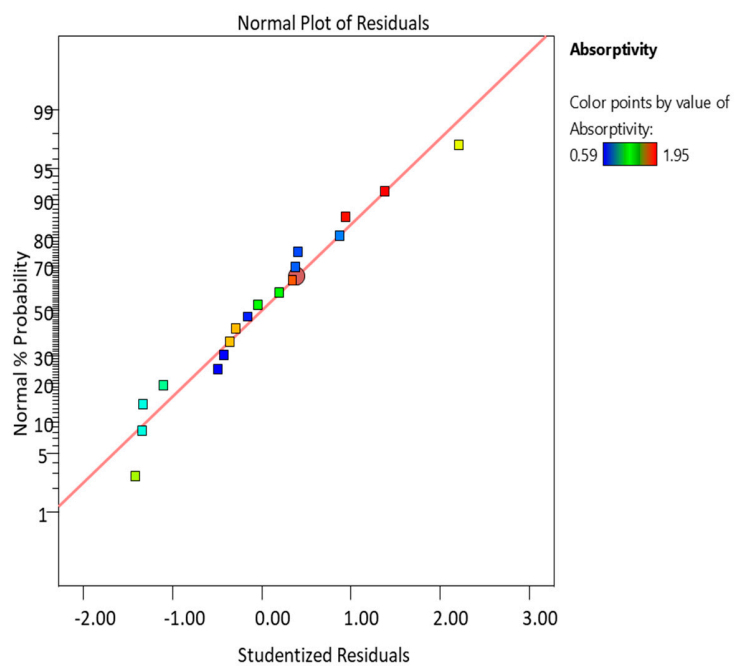


Figure S7: Normal probability plot of Studentized residuals of the switchgrass biocarbon composite's water absorptivity.

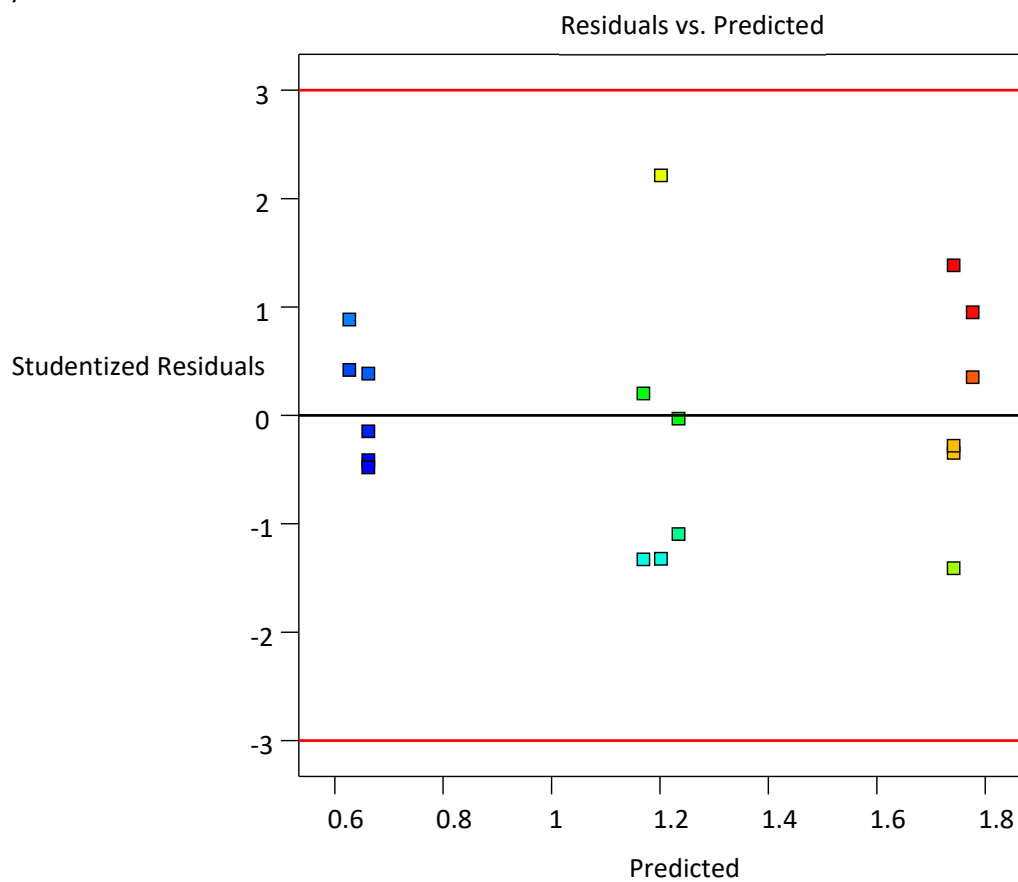


Figure S8: Residuals vs. predicted values plot of Studentized residuals of the switchgrass biocarbon composite's water absorptivity.

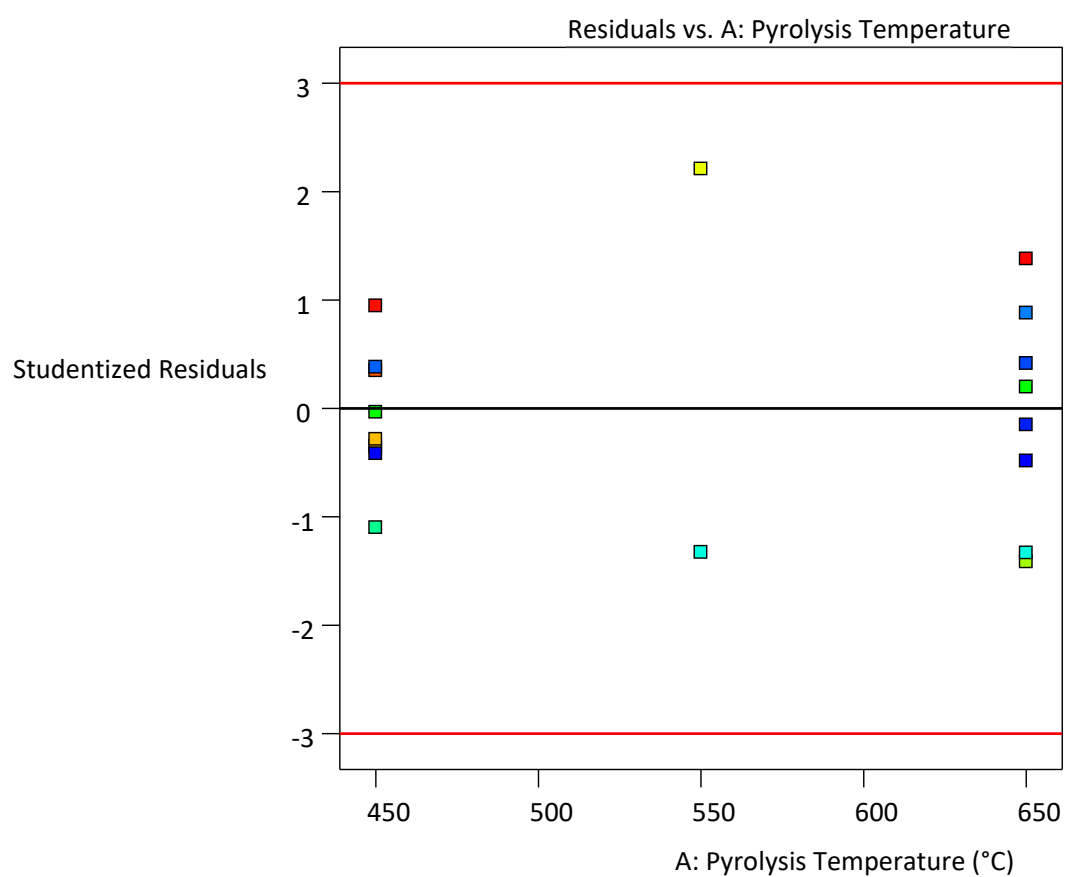


Figure S9: Residuals vs. pyrolysis temperature of Studentized residuals of the switchgrass biocarbon composite's water absorptivity.

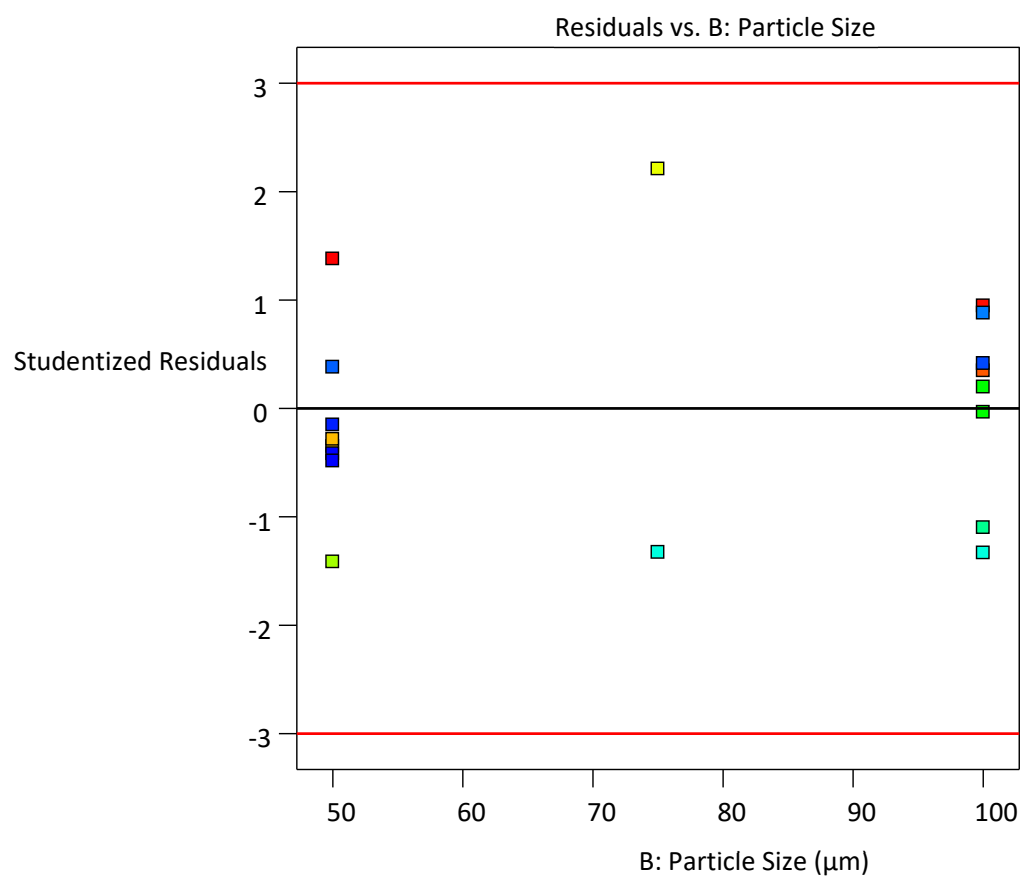


Figure S10: Residuals vs. particle size temperature of Studentized residuals of the switchgrass biocarbon composite's water absorptivity.

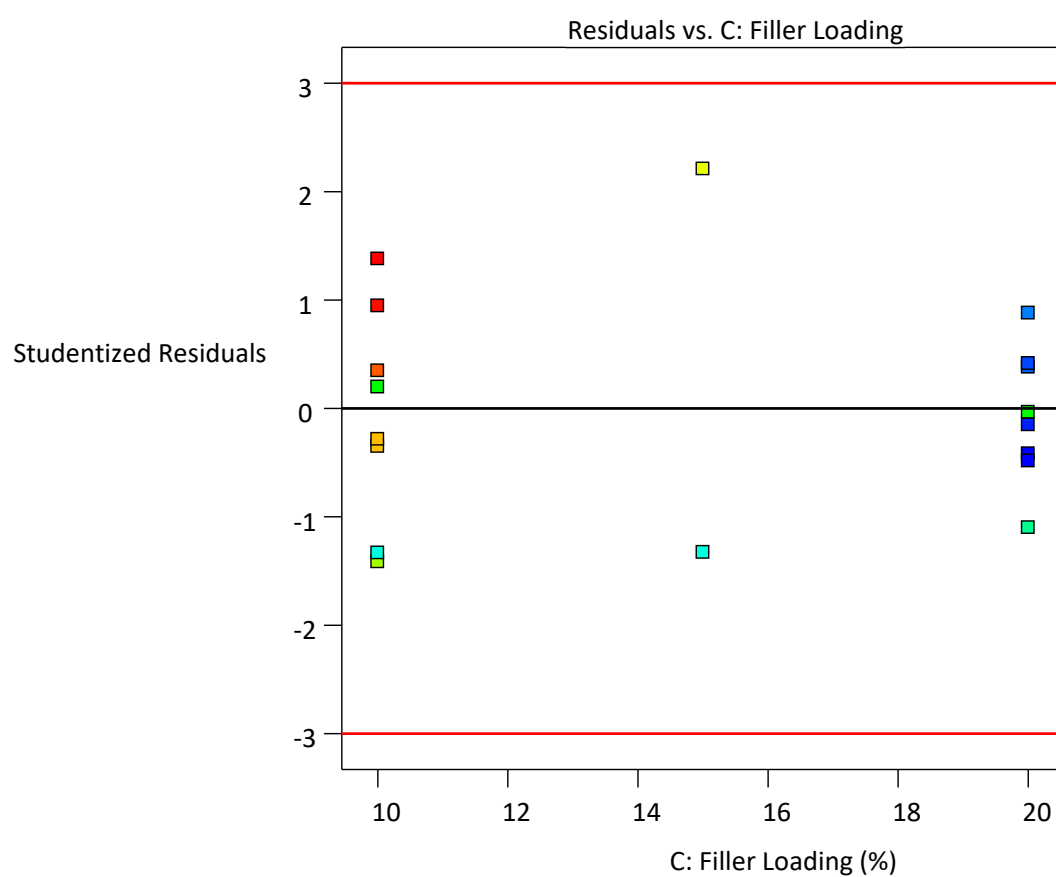


Figure S11: Residuals vs. filler loading of Studentized residuals of the switchgrass biocarbon composite's water absorptivity.

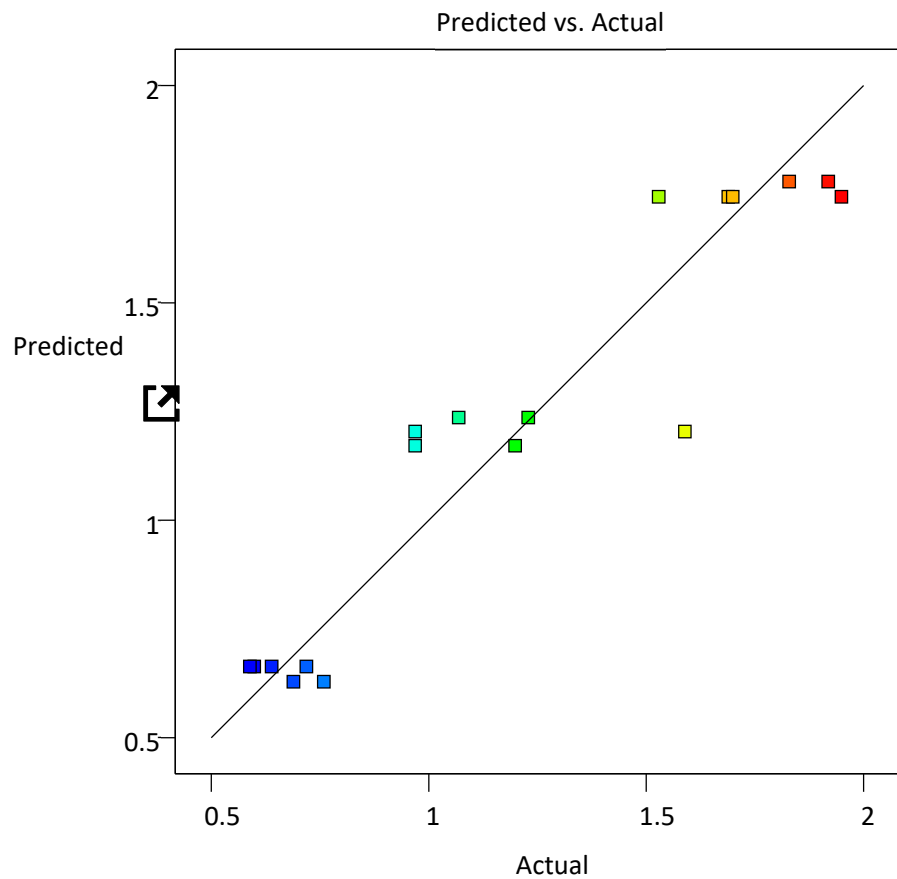


Figure S12: Predicted vs. actual of the switchgrass biocarbon composite's water absorptivity.

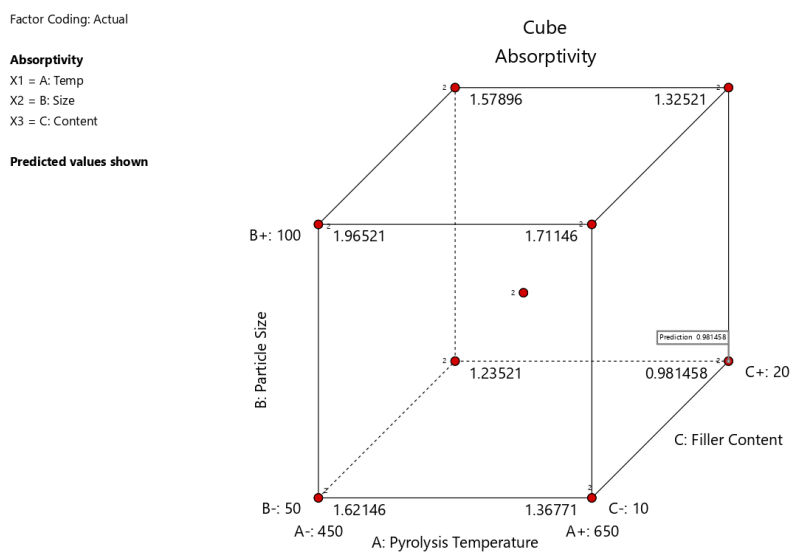


Figure S13: Cube plot showing all factors and the predicted water absorptivity values for the hemp biocarbon-filled hemp-reinforced polymer composites.

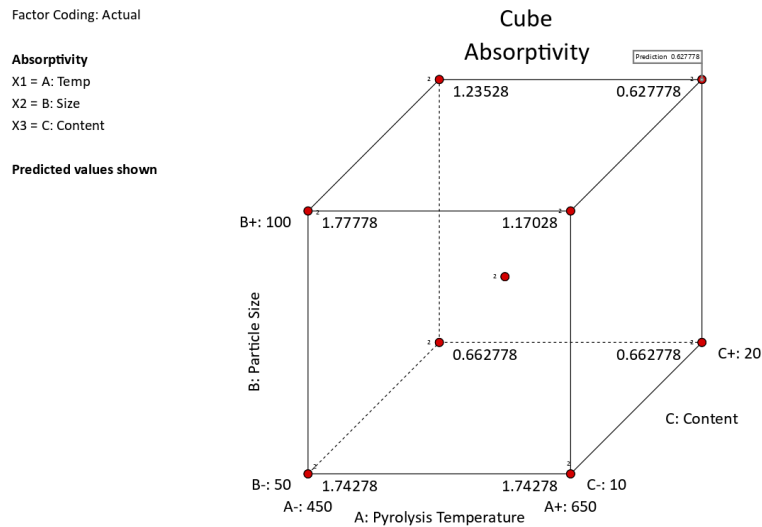


Figure S14: Cube plot showing all factors and the predicted water absorptivity values for the switchgrass biocarbon composites.

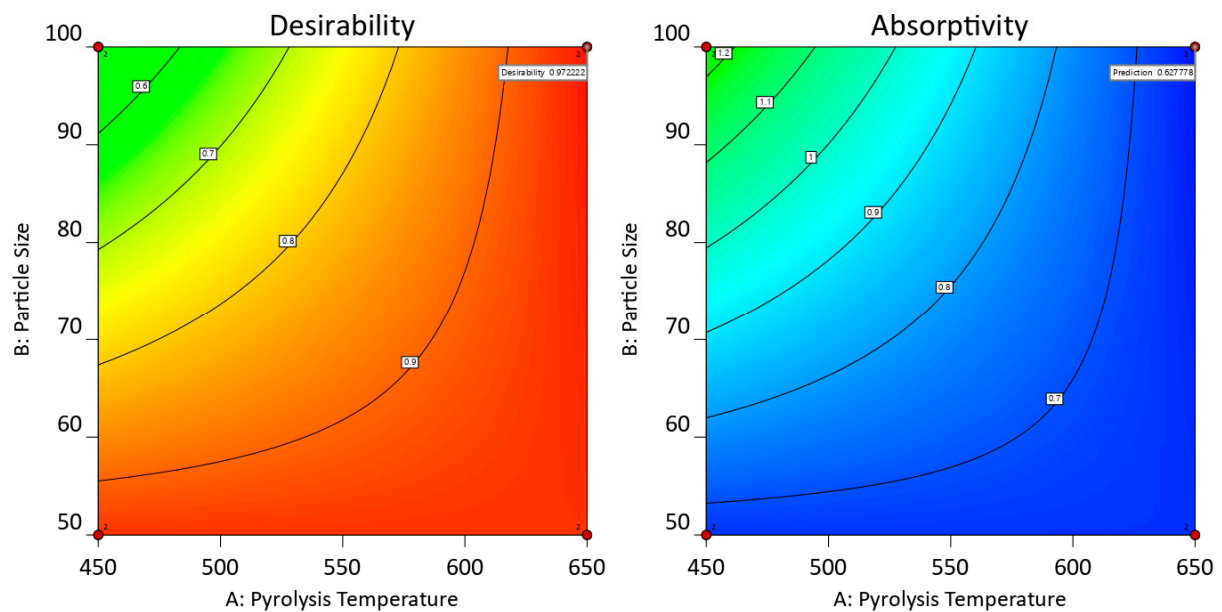


Figure S15: Contour plot showing the desirability of 0.972 with the predictability of 0.697 for the water absorptivity of switchgrass biocarbon-filled hemp-reinforced polymer composites when the filler loading is 20%.

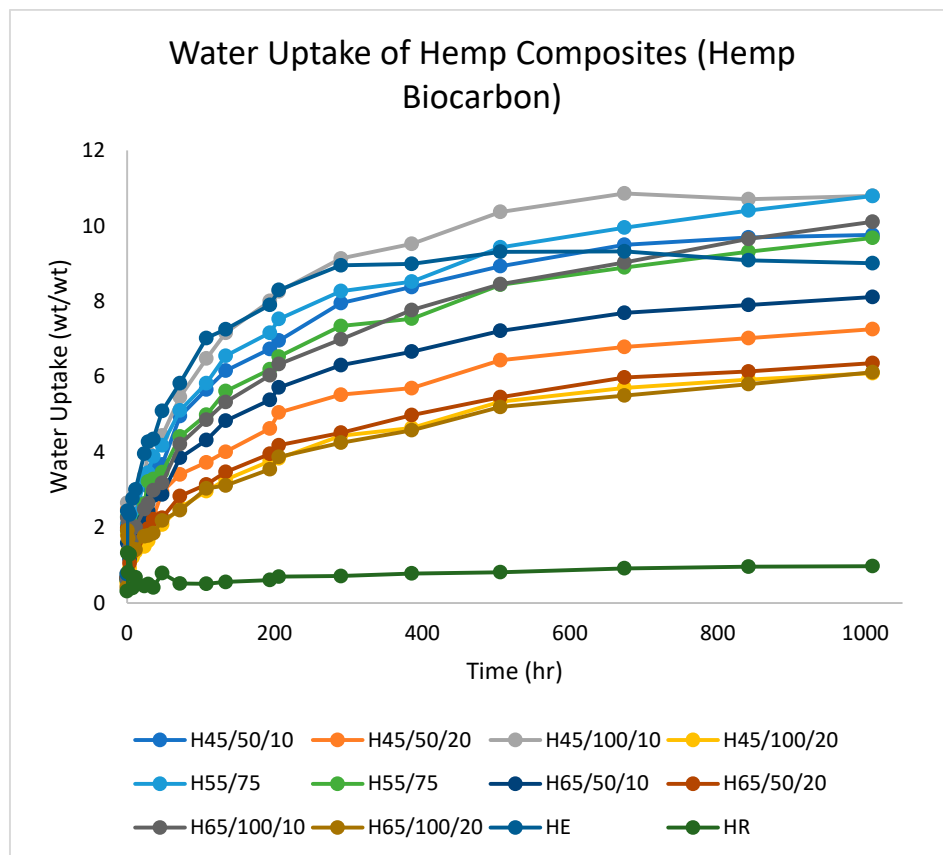


Figure S16: Water absorption curve of hemp composites with hemp biocarbon as a function of time (hr).

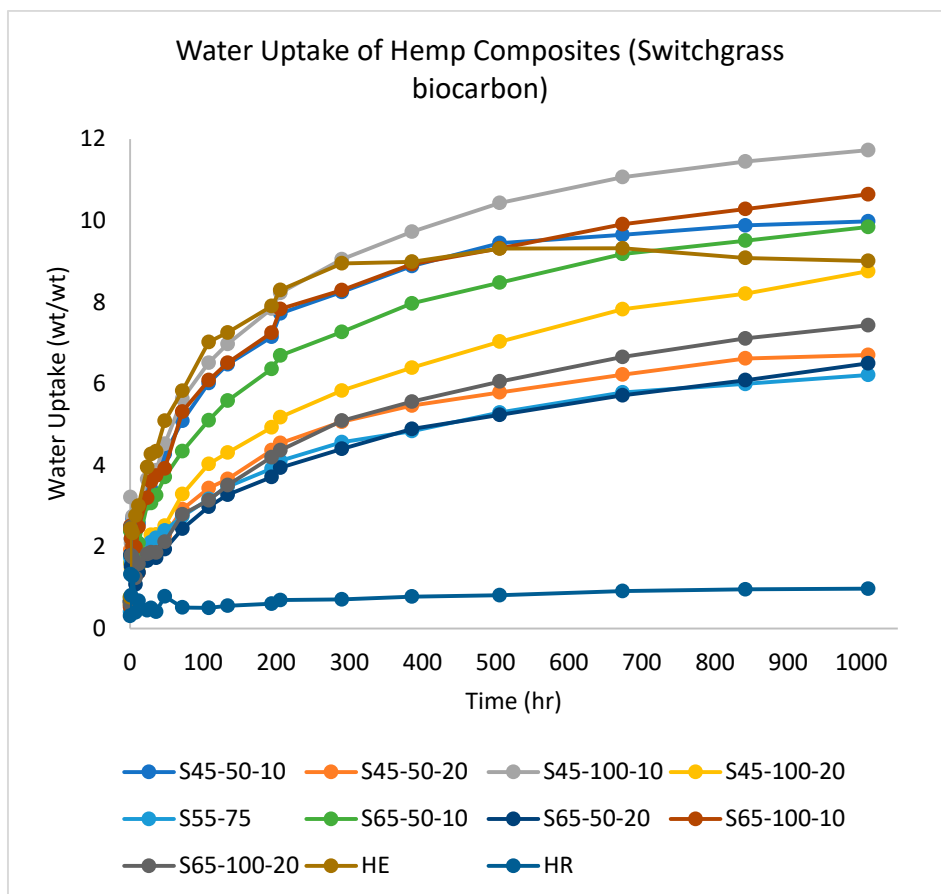


Figure S17: Water absorption curve of hemp composites with switchgrass biocarbon as a function of time (hr).