

Laser-Induced Graphene from biowaste materials

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Results and Discussion

Table S1. Powder and pellets parameters: t – pellet thickness (average of three dimensions with standard deviation), ρ – pellet density, d_{max} – maximum particle size of powders in granulometric analysis (average of three dimensions with standard deviation).

Sample	HSP	ASP	ASkP	CGP	LP	MPP	ChitP	SP
t [mm]	1.91 ± 0.01	1.83 ± 0.02	2.25 ± 0.04	2.21 ± 0.01	1.77 ± 0.01	2.16 ± 0.02	1.59 ± 0.00	1.59 ± 0.01
ρ [g cm ⁻³]	1.11	1.16	0.94	0.96	1.20	0.98	1.34	1.34
d_{max} [μm]	47.45 ± 1.49	32.36 ± 3.18	58.23 ± 4.14	52.23 ± 0.56	39.97 ± 0.95	55.61 ± 3.56	46.64 ± 3.34	44.31 ± 8.56

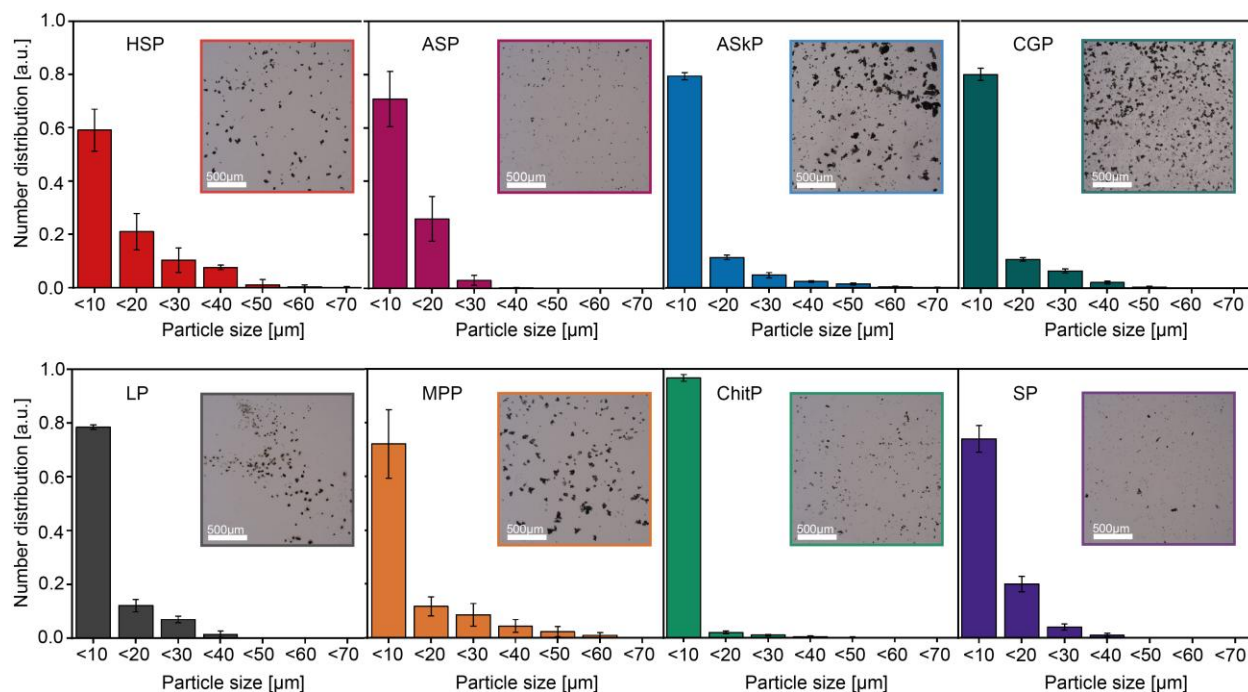


Figure S1. Particle size distribution plots normalized to total particle number (average of three dimensions with standard deviation), with a representative microscopic image.

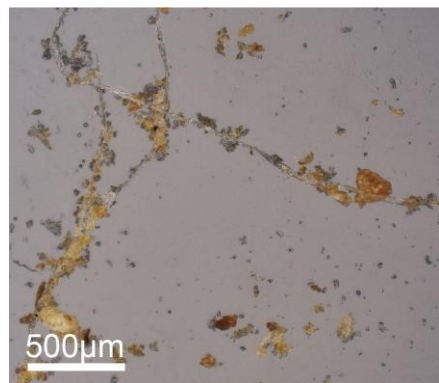


Figure S2. Optical microscope images of the big fiber in almond skin powder structure.

Table S2. Roughness: left pellet and LIG-pellet, right – composite and LIG-composite

Pellet	Rq [μm]	LIG	Rq [μm]
HSP	8.9	LIG-HSP	9.6
ASP	9.3	LIG-ASP	12
ASkP	26.2	LIG-ASkP	38.0
MPP	16.3	LIG-MPP	21.7
CGP	11.3	LIG-CGP	19.2
LP	8.6	LIG-LP	7.8
SP	10.9	LIG-SP	69.2
ChitP	12.1	LIG-ChitP	95.8

Composite	Rq [μm]	LIG	Rq [μm]
HSC	12.8	LIG-HSC	15.8
ASC	8.9	LIG-ASC	21.7
ASkC	27.4	LIG-ASkC	30.7
CGC	19.3	LIG-CGC	33.6
LC	17.8	LIG-LC	18.7

Table S3. Lignin chemical content of different types of biowaste.

Sample	Lignin [wt. %]	References
HSP	39.35 ± 0.14	[1–3]
ASP	29.50 ± 0.11	[4]
ASkP	21.50 ± 1.05	[5]
CGP	21.23 ± 4.45	[6–8]
MPP	8.6 ± 1.2	[9]

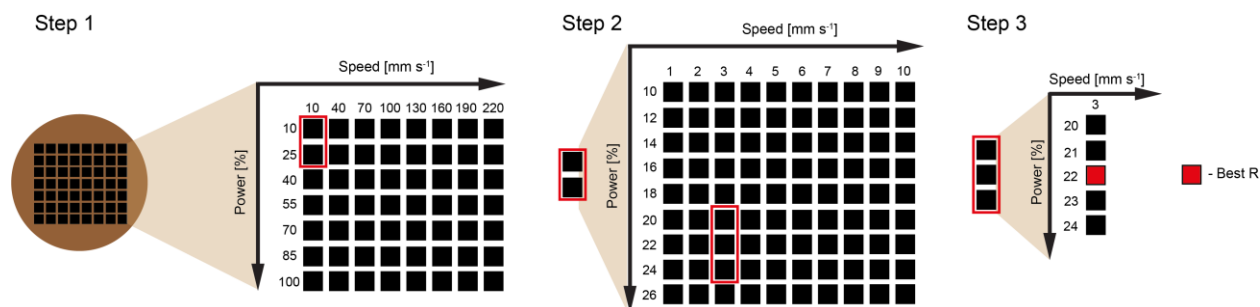
**Figure S3.** Details of the laser-scribed matrix used for laser parameters optimization. Step 1 - matrix with a wide speed and power step (30 mm s⁻¹ and 15%, respectively) Step 2 - die with a narrower speed and power step (1 mm s⁻¹ and 2%, respectively, the range of parameters varied depending on the matrix resistance values in Step 1 for each pellet), Step 3 - matrix with a power and speed step of 1 mm s⁻¹ and 1%, respectively, with subsequent selection of the best resistance – Best R.

Table S4. Z-average step between powder pellet structure and LIG scribed on the pellet surface (left), Z-average step between composite structure and LIG scribed on the composite surface (right) (average of three dimensions with standard deviation).

Pellet	Z-Average [μm]	Composite	Z-Average [μm]
HSP	33.4 ± 3.0	HSC	37.2 ± 1.2
ASP	29.4 ± 4.0	ASC	17.6 ± 1.4
ASkP	97.1 ± 21.5	ASkC	86.0 ± 15.3
MPP	112.8 ± 4.9	CGC	73.2 ± 6.2
CGP	124.8 ± 6.6	LC	5.5 ± 0.7
LP	4.8 ± 1.3		
SP	254.9 ± 47.9		
ChitP	233.2 ± 41.5		

Table S5. LIG sheet resistance on the surface of pellets (left), on the surface of composite (right) (average of three dimensions with standard deviation).

Pellet	R_s [$\Omega \text{ sq}^{-1}$]	Composite	R_s [$\Omega \text{ sq}^{-1}$]	LIG thickness [μm]
HSP	57.6 ± 16.5	HSC	219.7 ± 54.0	90 ± 8
ASP	103.7 ± 35.9	ASC	345.3 ± 24.1	179 ± 85
ASkP	226.7 ± 98.3	ASkC	1626.7 ± 512.9	115 ± 7.7
MPP	424.3 ± 169.0	CGC	3190 ± 6.2	68 ± 16
CGP	966.7 ± 409.2	LC	89.7 ± 18.5	122 ± 12
LP	38.7 ± 10.1			

Table S6. Comparison of ratios I_D/I_G and I_{2D}/I_{2G} between LIG obtained on the pellet (left) and LIG obtained on the composite (right).

Pellet	I_D/I_G	I_{2D}/I_G	Composite	I_D/I_G	I_{2D}/I_G
HSP	0.44 ± 0.04	0.42 ± 0.08	HSC	1.09 ± 0.06	0.37 ± 0.12
ASP	0.82 ± 0.14	0.29 ± 0.08	ASC	1.06 ± 0.16	0.18 ± 0.11
ASkP	0.93 ± 0.19	0.22 ± 0.06	ASkC	1.03 ± 0.11	0.39 ± 0.24
MPP	1.05 ± 0.03	0.20 ± 0.05	CGC	1.09 ± 0.08	0.22 ± 0.12
CGP	0.89 ± 0.06	0.11 ± 0.01	LC	1.26 ± 0.04	0.3 ± 0.09
LP	0.95 ± 0.09	0.25 ± 0.03			

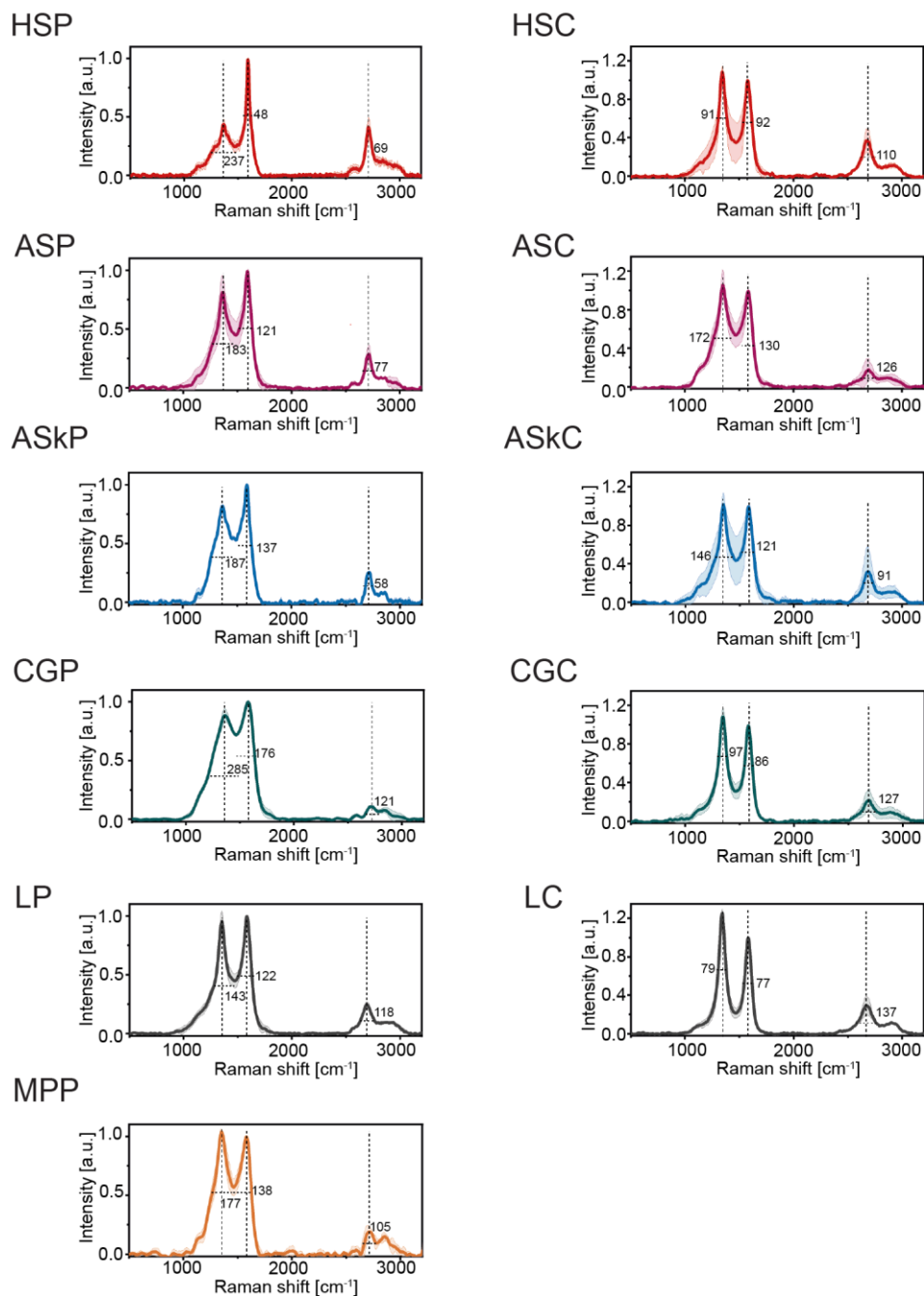


Figure S4. Raman spectra of the powder and composite samples. Vertical dashed lines indicate the peak centers, horizontal dashed lines represent the FWHM, with values reported on the plots. FWHM is extracted directly from the spectra or, in cases of broad peaks, from Lorentzian fits.

Table S7. Batch components mass for composites (round Petri dish size $D = 85$ mm)

Batch component	chitosan	filler (powder)	acetic acid, 2%	glycerol
Component mass [g]	0.79	1.6	40.8	1.3

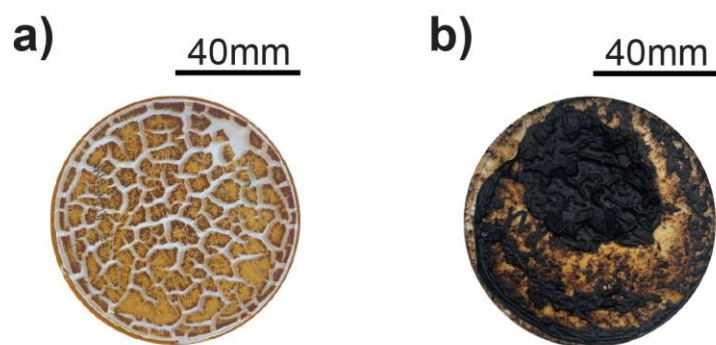


Figure S5. a) Mandarin peels composite (MPC) structure after drying. b) Lignin composite (LC) structure after drying.

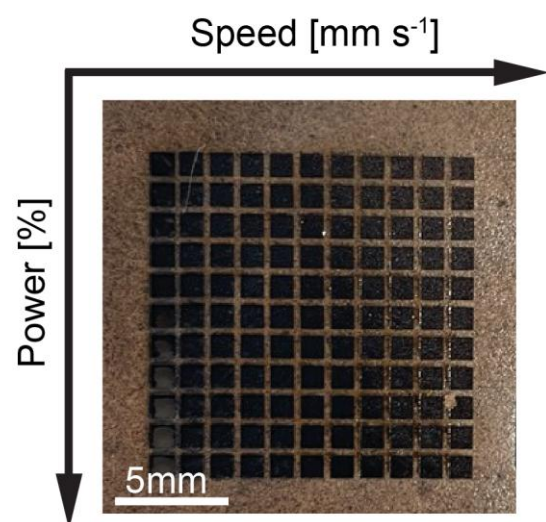


Figure S6. LIG matrix scribed on HSP (from **Figure 3a**) for laser parameters optimization.

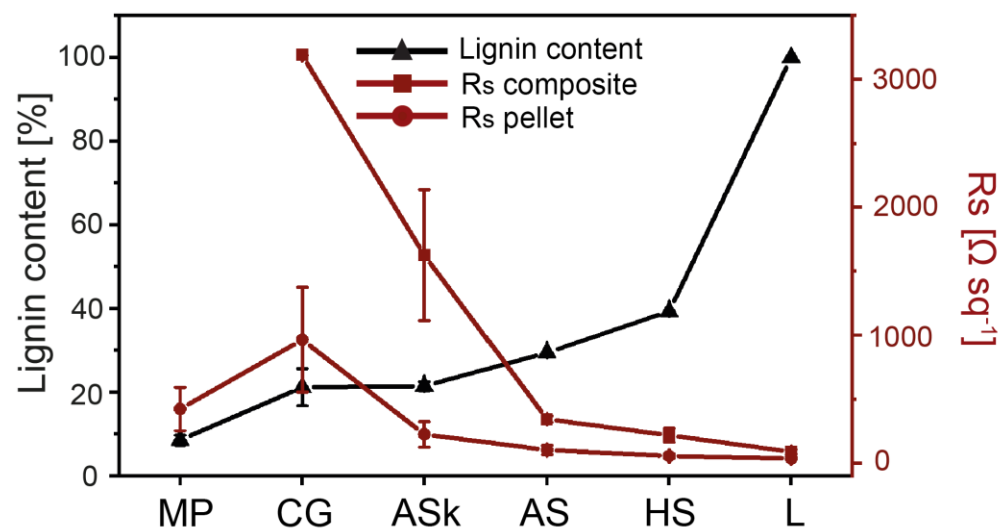


Figure S7. Sheet resistance R_s and lignin content of LIG-composite and LIG-pellets obtained from the various biowaste materials investigated in this study.

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