SUPPLEMENTARY FILES

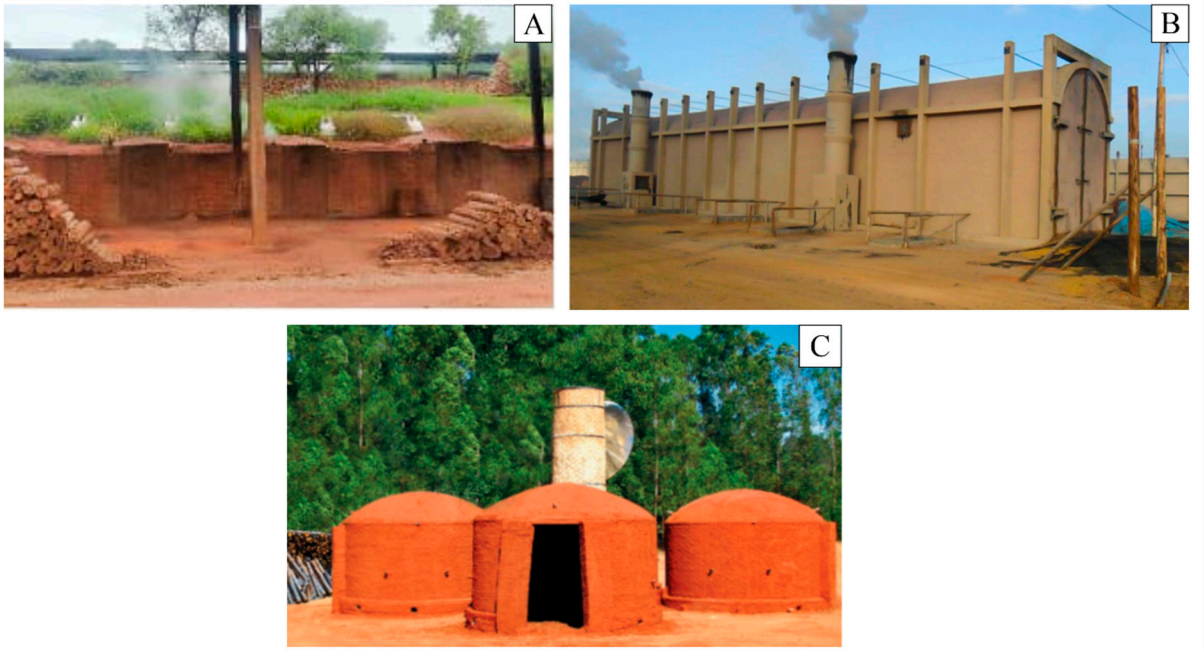


Figure S1. Encosta kiln (A), source: [1]; retangular kiln (B), source: [1]; fornalha kiln (C), source: [2].

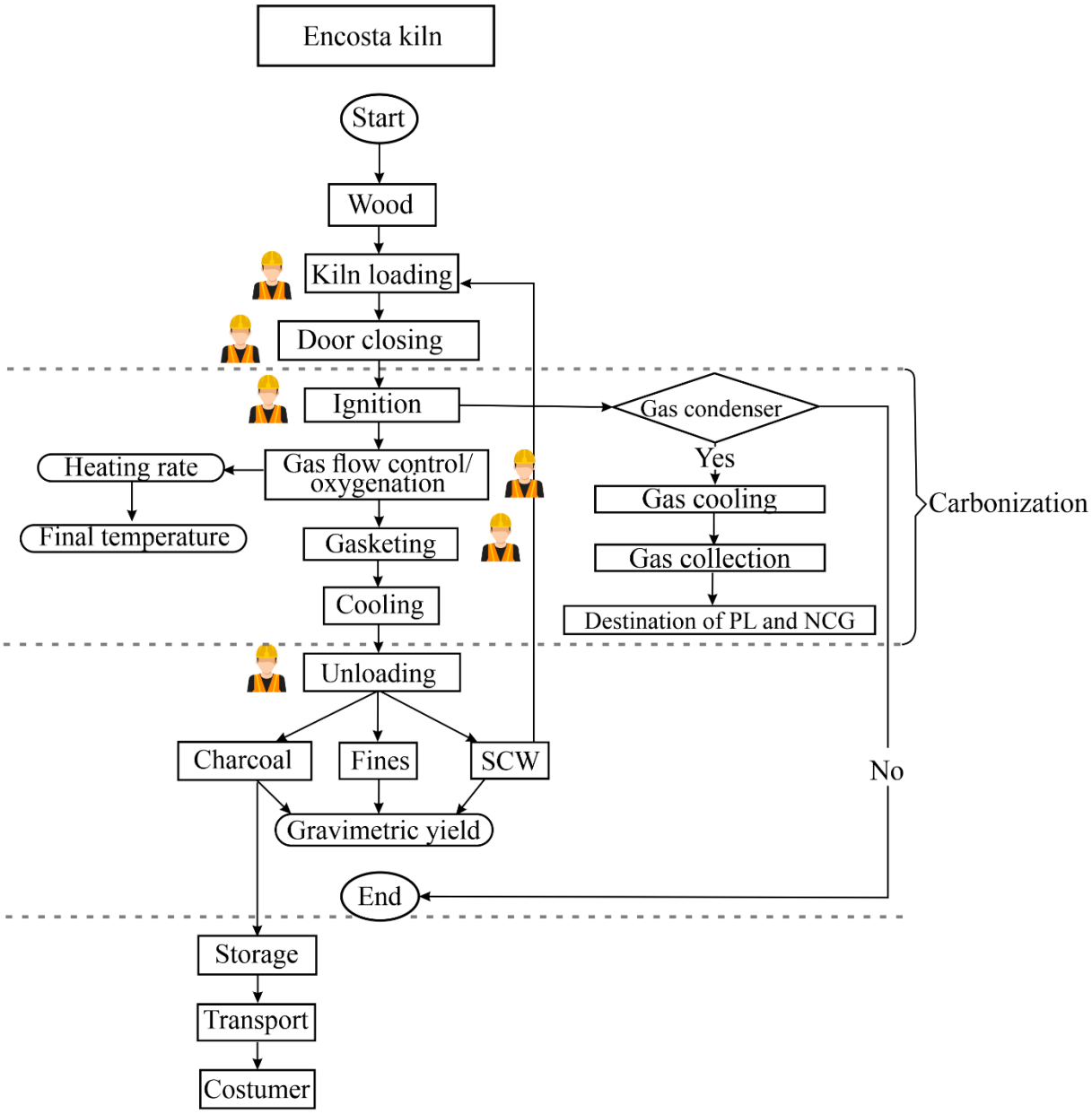


Figure S2. Flowchart of the charcoal production process in an encosta kiln.

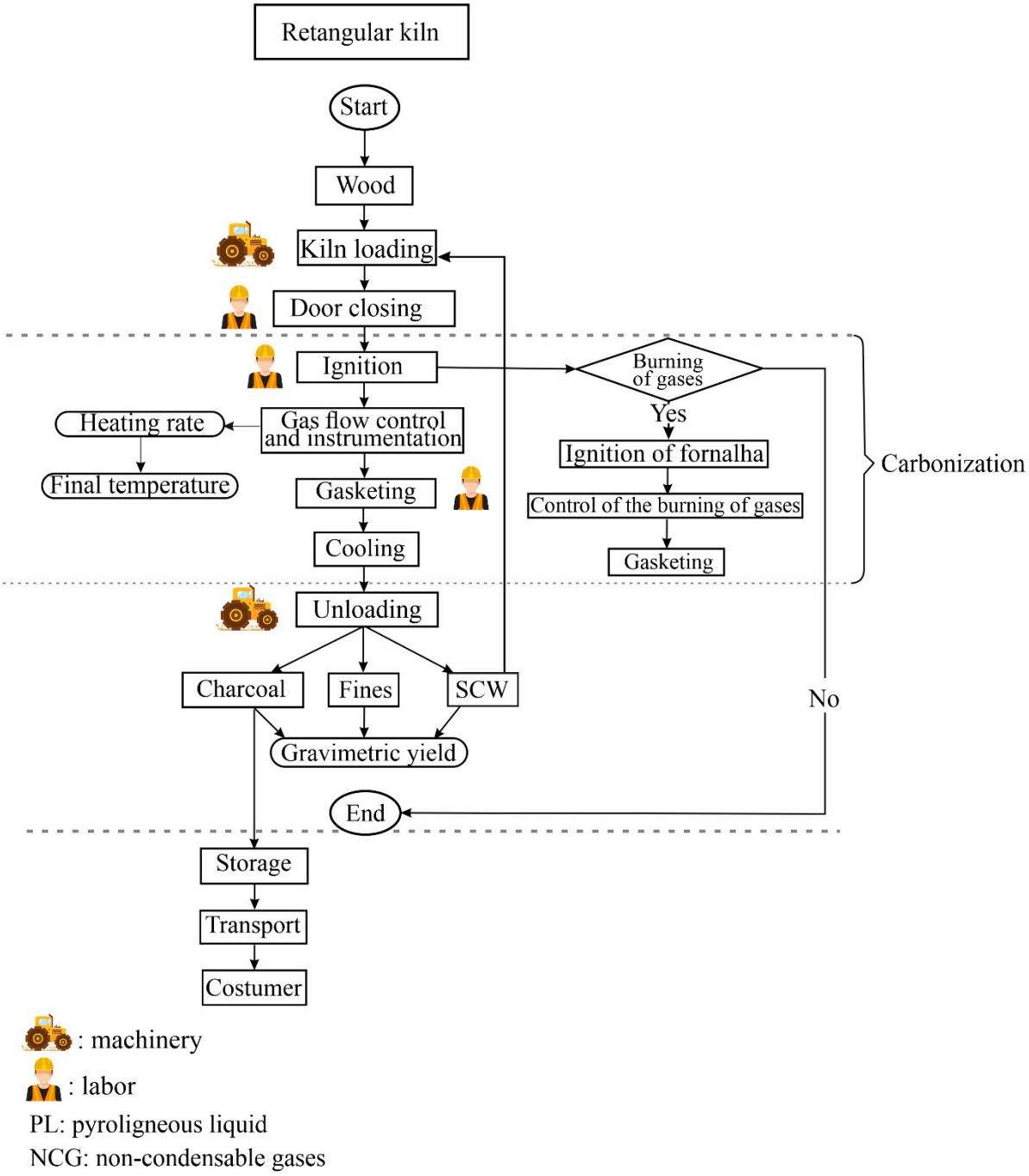


Figure S3. Flowchart of the charcoal production process in a rectangular kiln.

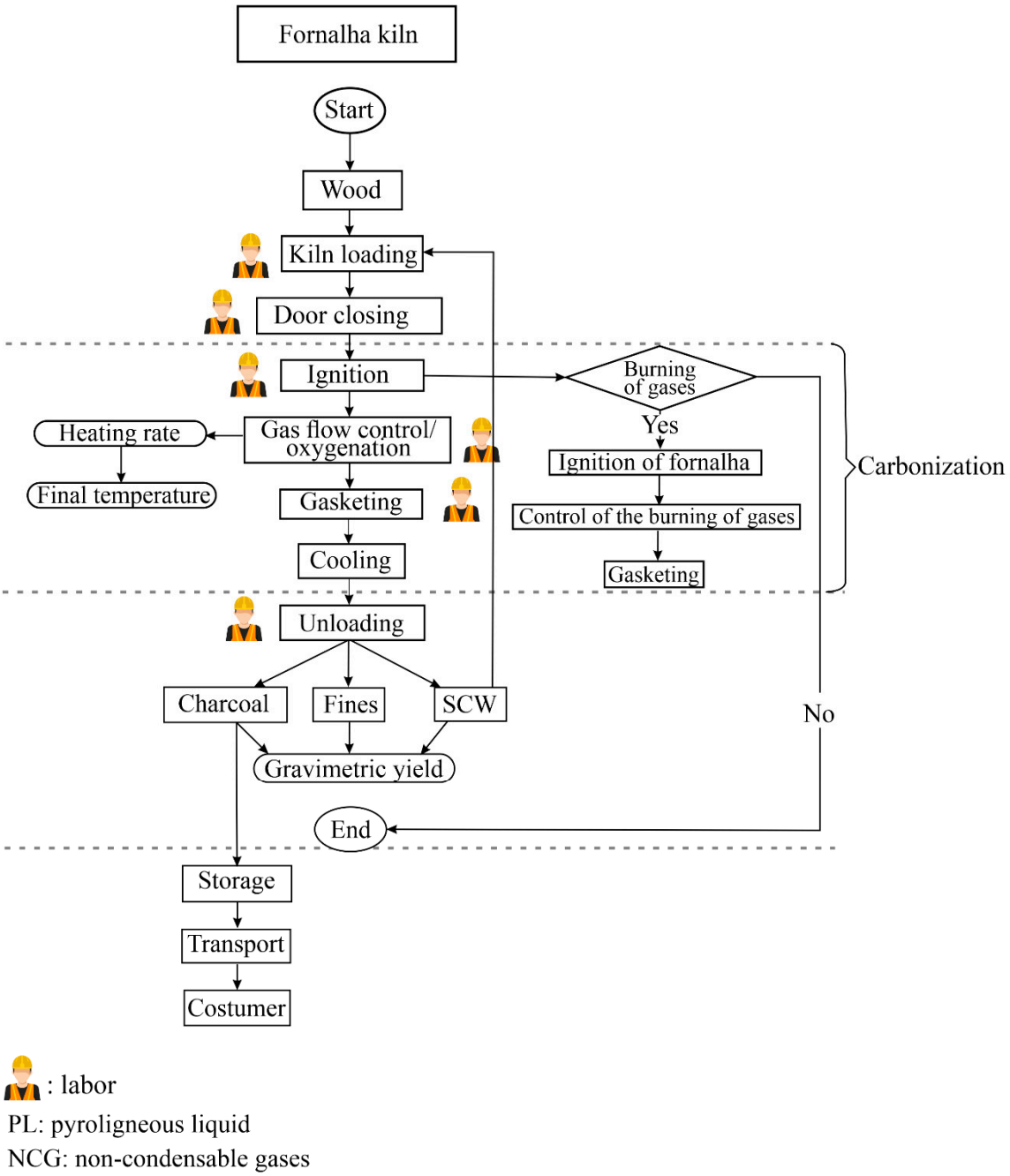


Figure S4. Flowchart of the charcoal production process in a fornalha kiln.

Table S1. Characteristics of the analyzed systems

System	Composition	Dimensions	Capacity	Mechanization
Encosta	Massive clay bricks	2.5 m_d and 2.5 m_h	7.00 m^3	-
Rectangular	Masonry in clay brick reinforced concrete, and steel	32 m_l x 4 m_w x 4 m_h	310 m^3	Loading and unloading
Fornalha	Ceramic solid bricks mortar coating	3.2 m_d x 2.2 m_a	8.5 m^3	Temperature control

Where: d = diameter; h = height; l: =length; w = width.

$$ECfines = UCVfines * Mfines \quad \text{Equation S1}$$

ECfines = Energy contained in the fines (MJ); UCVfines = useful calorific value of fines (MJ kg-1); Mfines = mass of fines generated in the process (kg).

$$ECscws = UCVscw * Mscw \quad \text{Equation S2}$$

ECscw = Energy contained in the semi-carbonized wood (MJ); UCVscw = useful calorific value of semi-carbonized wood (MJ kg^{-1}); Mscw = mass of semi-carbonized wood generated in the process (kg).

$$ECpl = UCVpl * Mpl \quad \text{Equation S3}$$

ECpl = Energy contained in the pyroligneous liquid (MJ); UCVpl = useful calorific value of the pyroligneous liquid (MJ kg^{-1}); Mpl = mass of the pyroligneous liquid (kg).

$$ECncg = (HCVCO_2 * MCO_2) + (HCVCO * MCO) + (HCVH_2 * MH_2) + (HCVCH_4 * MCH_4) \quad \text{Equation S4}$$

ECncg = Energy contained in non-condensable gases (MJ); $HCVCO_2$ = higher calorific value of CO_2 (MJ kg^{-1}); MCO_2 = mass of CO_2 (kg); HCVCO = higher calorific value of CO (MJ kg^{-1}); MCO = mass of CO (kg); $HCVH_2$ = higher calorific value of H_2 (MJ kg^{-1}); MH_2 = mass of H_2 (kg); $HCVCH_4$ = higher calorific value of CH_4 (MJ kg^{-1}); MCH_4 = mass of CH_4 (kg).

Table S2. The theoretical model proposed for the energy input flow of the materials of the encosta kiln and the fornalha kiln.

Wood dry basis (kg)	UCV (MJ kg^{-1})	Labor – kiln loading	MO1 (MJ h^{-1})	Labor - operator	MO2 (MJ h^{-1})	Total contained Energy (MJ)
1/Ych	Wood UCV	Total hours of the labor to kiln the wood/mass of charcoal produced (kg)	2.20	Total hours of labor/mass of charcoal produced (kg)	1.18	(Wood in dry basis*UCV) + (Labor kiln loading*HCV) + (Labor operator*HCV)

Where: Ych = gravimetric yield of charcoal (%), UCV = useful calorific value (MJ kg^{-1}), MO1 = physical effort to carry out the loading and unloading activity (MJ h^{-1}), MO2 = physical effort to the execution of the process monitoring activity (MJ h^{-1}).

Table S3. The theoretical model proposed for the energy flow of the materials of the rectangular kiln.

Wood (kg)	UCV (MJ kg^{-1})	Specialized machine (L)	HCV (MJ h^{-1})	Labor - machine	MO3 (MJ h^{-1})	Labor - operator	MO2 (MJ h^{-1})	Total contained Energy (MJ)
1/Ych	Wood UCV	Machine consumption/mass of charcoal produced (kg)	38.35[A]	Total hours of the labor operating the machine/mass of charcoal produced (kg)	1.10	Total hours of labor/mass of charcoal produced (kg)	1.18	(Wood in dry basis*UCV)+(Mechanized labor *HCV))+(Labor in operating machine*HCV)+ (Labor operator*HCV)

Where: Ych = gravimetric yield of charcoal (%), UCV = useful calorific value (MJ kg^{-1}), A = higher calorific value of diesel oil, MO3 = physical effort in operating the specialized machine (MJ h^{-1}), MO2 = physical effort to perform the process monitoring activity (MJ h^{-1}).

Table S4. Energy flow model for output materials in all types of system

Charcoal (t)		**UCV (MJ kg^{-1})**		**SCW (kg)**		**HCV (MJ kg^{-1})**	**Pyroligneous Liquid**	**HCV (MJ kg^{-1})**	**Fines**	**HCV (MJ kg^{-1})**
1		Charcoal UCV		% semi-carbonized wood * wood mass		78% of HCV of charcoal	% of PL * wood mass	HCV of LP (5255)	% of fines*UCV of charcoal	HCV of charcoal
CO_2	**HCV (MJ kg^{-1})**	**CO**	**HCV (MJ kg^{-1})**	**H_2**	**HCV (MJ kg^{-1})**	**CH_4**	**HCV (MJ kg^{-1})**	**Total contained Energy (MJ)**		
(97.41[A]* dry wood mass)/1000	0	(43.2[B]* dry wood mass)/1000	10,10	(0.36[C]* dry wood mass)/1000	141.65	(4.5* dry wood mass)/1000	55.47[D]	(charcoal*UCV)+(SCW*HCV+(LP* HCV)+(fines* HCV)+(massCO2* HCV)+(CO* HCV)+(H_2* HCV)+(CH_4* HCV)		

Where: UCV = useful calorific value (MJ kg^{-1}), HCV = higher calorific value (MJ kg^{-1}), A = emission of 97.41 (kg t^{-1} dry wood) of CO_2 (carbon dioxide), B = emission of 43.2 (kg t^{-1} dry wood) of CO (carbon monoxide), C = emission of 0.36 (kg t^{-1} dry wood) of H_2 (Hydrogen), D = emission of 4.5 (kg t^{-1} dry wood) of CH_4 (methane).

Table S5. Variables used for sensitivity analysis

Material	Variables	Encosta kiln		Rectangular kiln		Fornalha kiln	
		LCL	UCL	LCL	UCL	LCL	UCL
Inputs							
Wood	Moisture (%)	10.00	35.00	10.00	35.00	10.00	35.00
	Density (kg m^{-3})	400.00	550.00	400.00	550.00	400.00	550.00
	UCV (MJ kg^{-1})	18.82	19.75	18.82	19.75	18.82	19.75
	Mass (kg) - dry basis	3,188.25	3,644.74	3,007.52	3,508.77	3,001.20	3,291.64
	Kiln capacity (m^3)	6	8	307	312	8.5	10.5
System	Ych (%)	28.00	32.00	30.00	35.00	31.00	34.00
	Labor (h) – kiln loading	7.14	13.72	-	-	7.59	13.54
	Labor (h) - operator	3.57	6.86	1.38	2.27	3.79	6.77
	Labor (h) - operator	-	-	0.16	0.27	-	-
	Machinery (L)	-	-	1.13	1.87	-	-
Outputs							
Charcoal	Moisture (%)	1.00	7.00	1.00	7.00	1.00	7.00
	Density (kg m^{-3})	215.00	229.00	220.00	251.00	215.00	251.00
	Production – dry basis (kg)	930.00	990.00	930.00	990.00	930.00	990.00
	UCV (MJ kg^{-1})	29.73	36.26	28.96	31.55	28.96	31.55
SCW	Product (%)	8.00	10.00	1.00	3.00	1.00	3.00
	UCV (MJ kg^{-1})	28.45	34.96	27.67	30.26	27.68	30.26
	Mass (kg)	307.20	577.30	30.08	105.26	240.10	329.16
Fines	Product (%)	15.00	25.00	8.00	15.00	12.00	18.00
	UCV (MJ kg^{-1})	22.19	27.27	21.58	23.60	21.59	23.60
	Mass (kg)	576	1443.25	240.60	526.32	360.14	592.60
PL	Product (%)	2.30	3.50	2.30	3.50	2.30	3.50
	Mass (kg)	88.32	202.06	69.17	122.81	69.03	115.21
NCG (kg t^{-1})	CO_2	373.22	560.79	292.15	340.84	291.54	319.75
	CO	140.955	212	110.9	128.805	110.25	120.85
	CH_4	14.385	21.63	11.315	13.145	11.245	12.33
	H_2	1.38	2.08	1.08	1.26	1.08	1.18

Where: LCL = lower control limit; UCL = upper control limit; Ych = gravimetric yield of charcoal (%); HVC = higher calorific value (MJ kg^{-1}); UCV = useful calorific value (MJ kg^{-1}); CO_2 = carbon dioxide (kg t^{-1}); CO = carbon monoxide; CH_4 = methane; H_2 = hydrogen.

References

[1] F.F. Bernardes, Desempenho energético de diferentes processos de produção de carvão vegetal, 2019.

[2] M. do M.A. Brasil, Produção sustentável de carvão vegetal: manual de construção sistemas fornos, fornalha, Brasília, 2019.