ESTEP SPRING DISSEMINATION EVENT

17-18 FEBRUARY 2026 - BRUSSELS (BELGIUM)

CROSSCUT - Results about biochar application in sintering process

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Łukasiewicz – GIT

ESTEP

Table of content

Łukasiewicz
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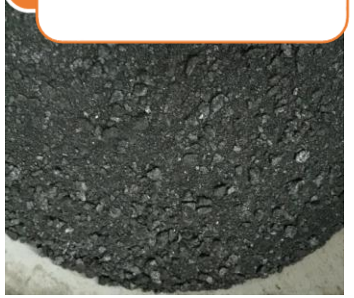
Instytut
Technologiczny

Results about biochar application in sintering process

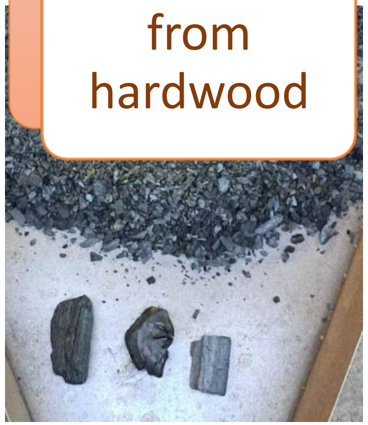
MATERIALS FOR TESTING

Used materials

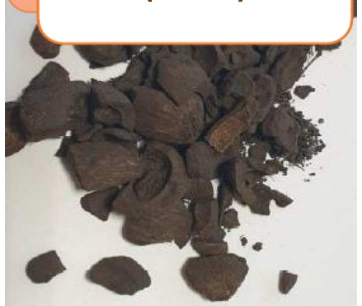
Coke breeze



Charcoal from hardwood



Raw Palm Kernel Shell (PKS)



Palm Kernel Shell (PKS) char

Wood pellets char

Wood chips char

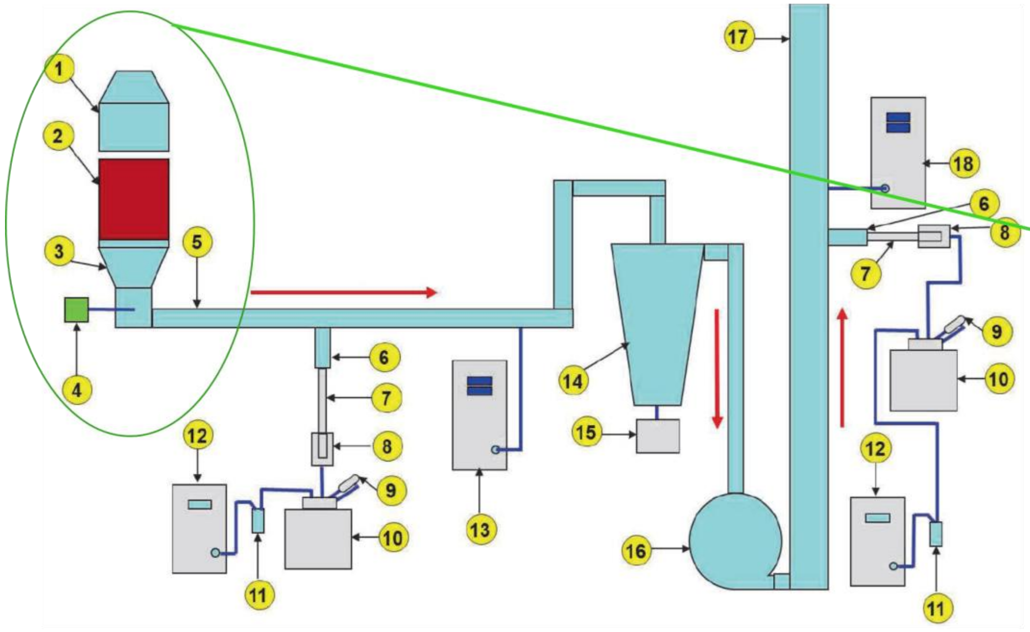
Results about biochar application in sintering process

CHEMICAL ANALYSIS OF MATERIALS

	C content, %	Volatiles content, %	Ash content, %	S content, %
Coke breeze	82,90	1,57	11,5	0,53
Charcoal	In progress			
Raw PKS	41,24	64,88	7,69	0,04
Wood chips char	In progess			
PKS char	91,18	1,84	17,25	0,03
Pellet char	92,50	3,39	3,85	0,05

Results about biochar application in sintering process

LINE FOR SEMI-INDUSTRIAL SIMULATION OF IRON ORES SINTERING



1. Burner
2. Sintering pan
3. Temperature measurement
4. Collection of dusts before the ceramic filter inlet
5. Flue gas pipeline
6. Sampling point (connector)
7. Probe with a thermostatic cloak
8. Celluloid filter (casing)
9. Absorber of organic compounds from gas phase
10. Cooler with a condensate collecting bottle
11. Moisture absorber
12. Suction pump with control system
13. Analyzer—continuous analysis on the "dirty" side
14. Ceramic filter (equipped with sorbent injection)
15. Collection of fluids from the ceramic filter tank
16. Exhaust fan
17. Chimney
18. Analyzer—continuous analysis on the "clean" side

Parameter	Unit	Value
Area of the sinter pot	m^2	0,19
Bed height	cm	55
Bedding	kg	10
Total of prepared wet mix	kg on wet	200
ΔP during ignition	Pa	8000
ΔP during cooking	Pa	17000
Time of ignition hood pre-heating	s	120
ΔP during pre- heating	Pa	3000
Time of ignition	s	90
Total volume of natural gas for ignition	m^3	0,789
Ratio air/gas		10
O2 in fumes of ignition hood	%	13,5
ΔP during ignition	Pa	8000
Natural gas PCI	MJ/m^3	36,193
Energy of ignition	MJ	28,56
Example for 110 kg sinter	MJ/ts	259,60

Results about biochar application in sintering process

LINE FOR SEMI-INDUSTRIAL SIMULATION OF IRON ORES SINTERING

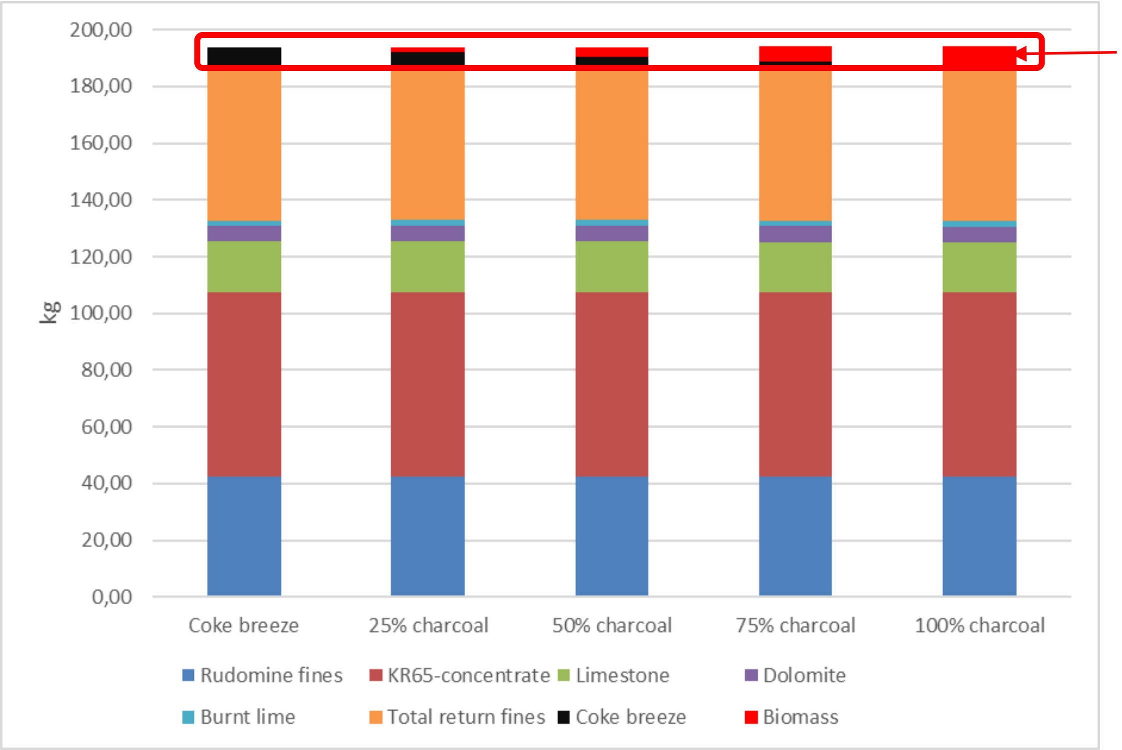
Results about biochar application in sintering process

Sintering trials results

Results about biochar application in sintering process

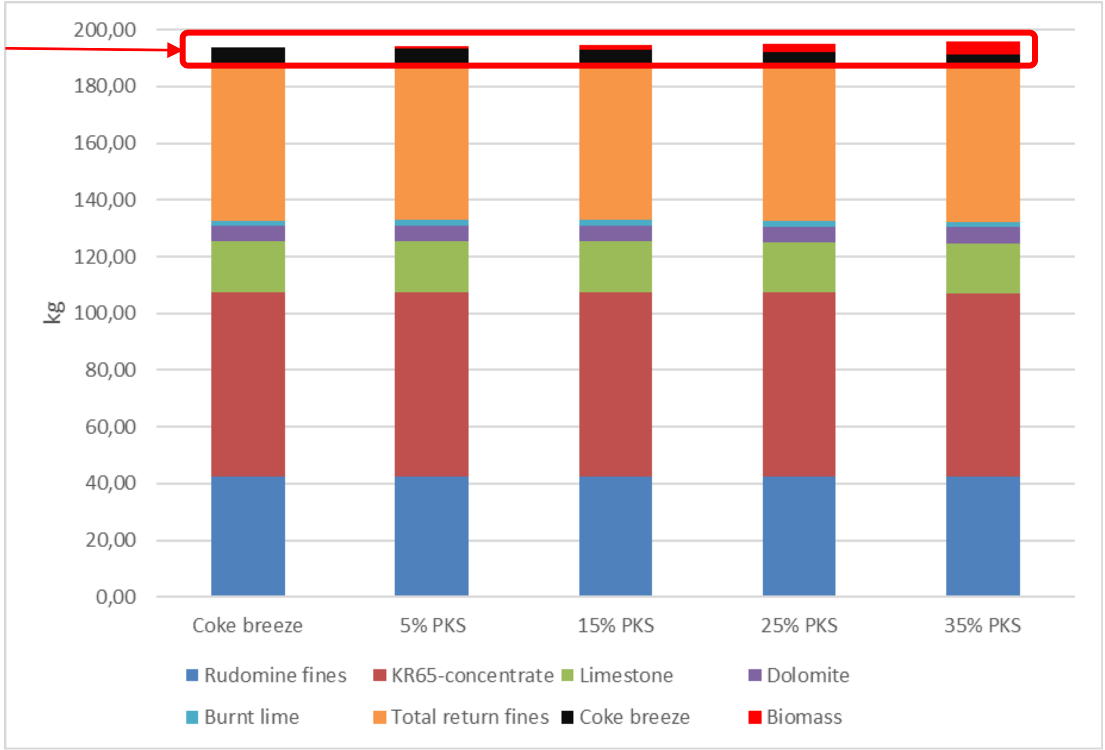
EXAMPLE OF THE COMPOSITION OF THE SINTERING MIXTURE

Charcoal



fuel

Raw PKS

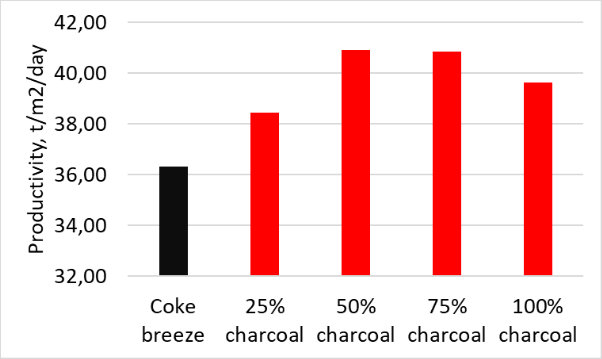


The fuel fraction in the sintering blend is approximately 5%. Complete substitution with charcoal is feasible, whereas PKS can be used up to a maximum of 35% due to its high content of oily components, which increases the risk of system clogging and potential ignition within the gas-cleaning equipment.

Results about biochar application in sintering process

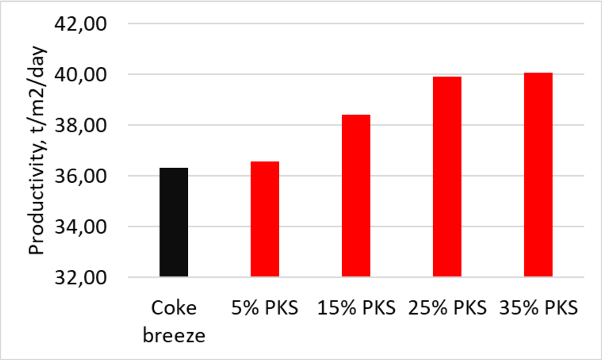
PRODUCTIVITY

Charcoal



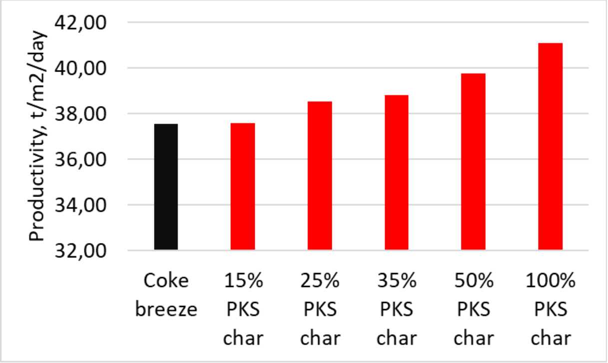
Charcoal substitution increases productivity up to a 50% replacement level; further addition reduces productivity but still maintains values above those of coke breeze

Raw PKS



Productivity rises progressively with increasing raw PKS substitution and remains consistently higher than for coke breeze

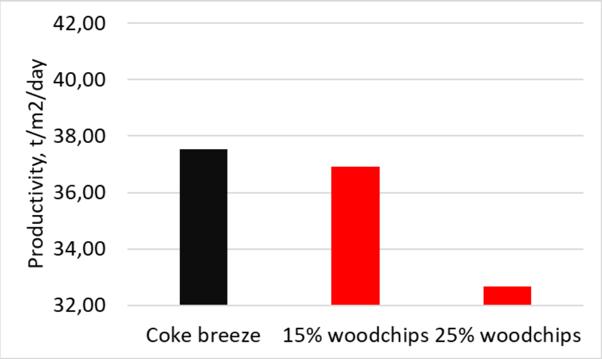
PKS char



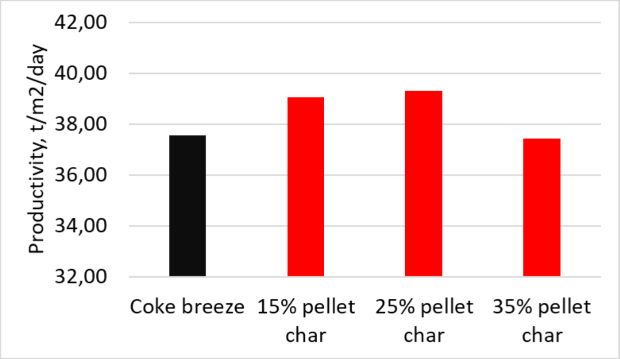
Productivity increases with rising PKS char substitution and remains higher than for coke breeze

Wood chips char

Wood-chips char reduces productivity, yielding values lower than those of coke breeze



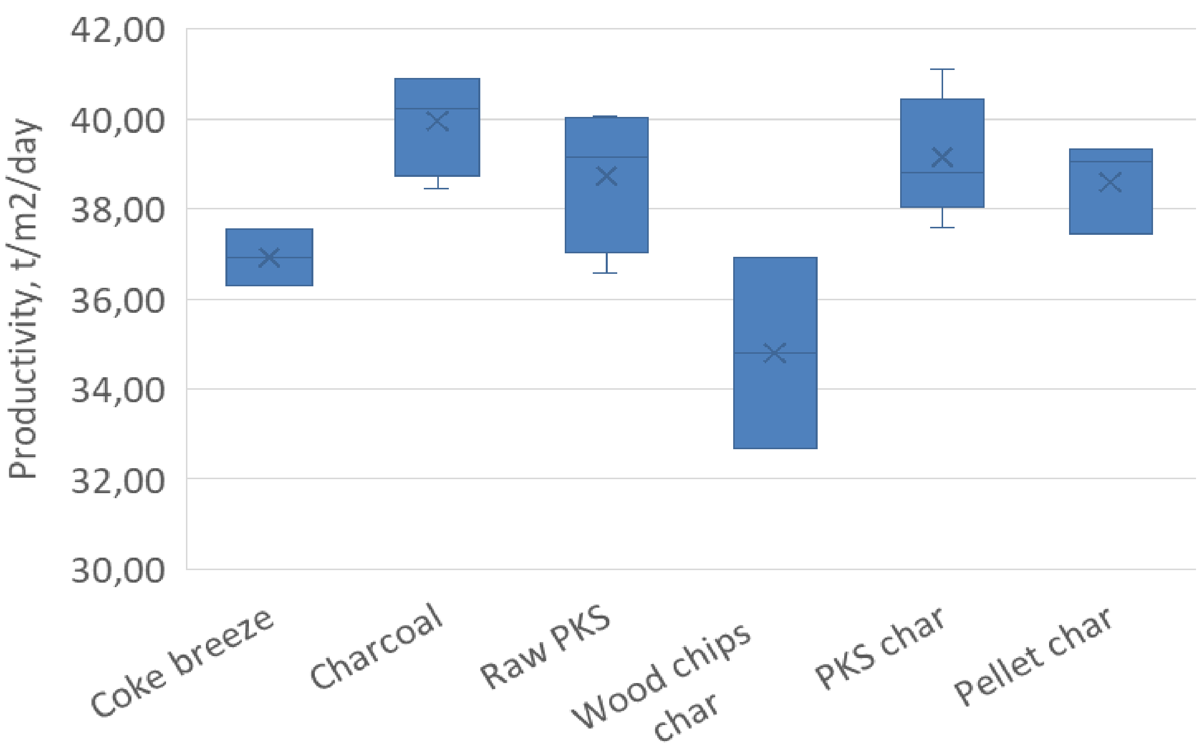
Pellet char



Pellet char enhances productivity up to a 25% substitution level; further replacement decreases productivity

Results about biochar application in sintering process

PRODUCTIVITY

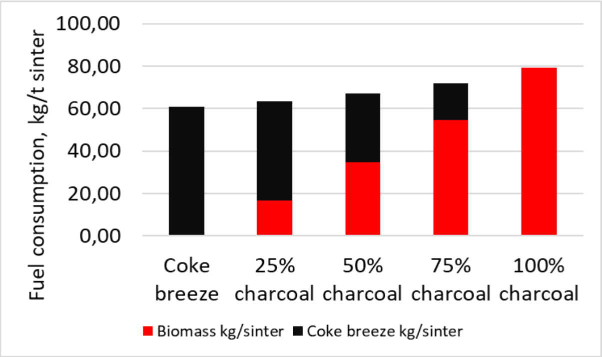


The results show that charcoal, raw PKS, PKS char, and pellet char all yield higher sinter productivity than coke breeze, with charcoal and raw PKS achieving the highest values, whereas wood-chips char is the only substitute exhibiting a pronounced reduction in productivity.

Results about biochar application in sintering process

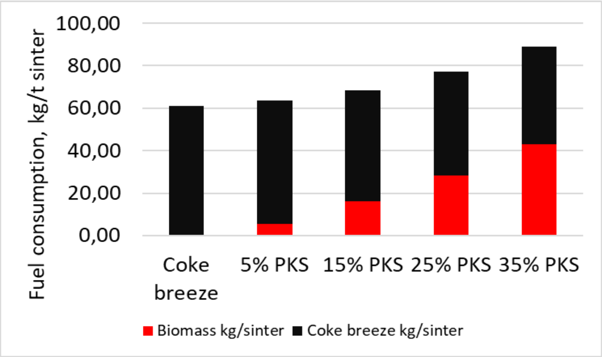
SOLID FUEL CONSUMPTION

Charcoal



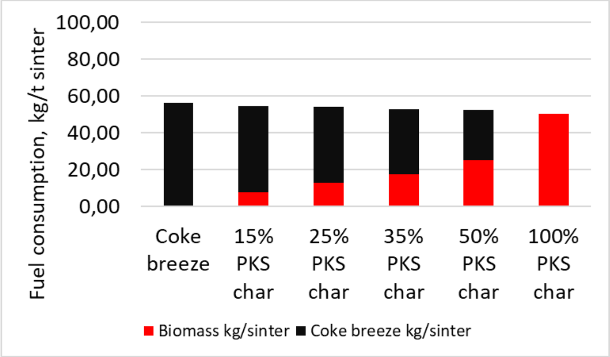
Charcoal substitution increases solid fuel consumption due to its lower carbon content relative to coke breeze, with feasible replacement levels up to 100%

Raw PKS



Raw PKS substitution similarly elevates solid fuel consumption because of its reduced carbon content, and its maximum practical replacement ratio is 35%

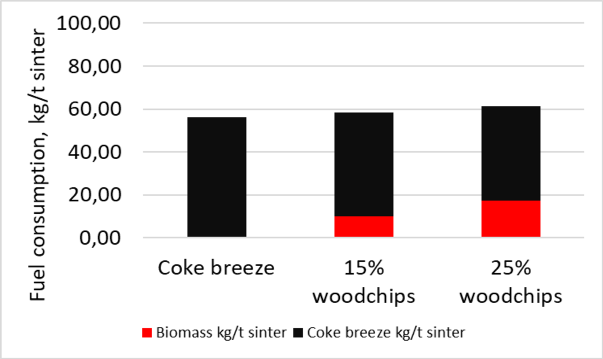
PKS char



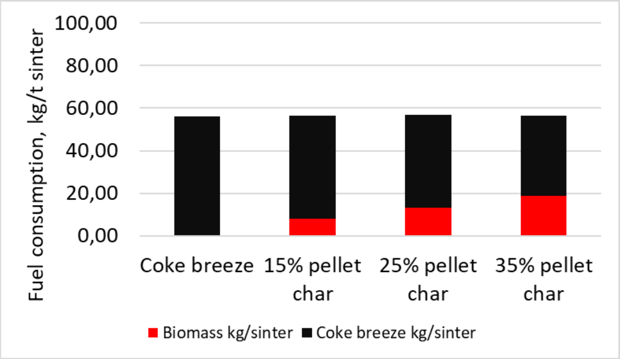
PKS char lowers solid fuel consumption, reflecting its higher carbon concentration, and can be introduced at substitution rates up to 100%

Wood chips char

Wood-chips char causes a slight increase in solid fuel consumption, with permissible substitution levels reaching about 25%



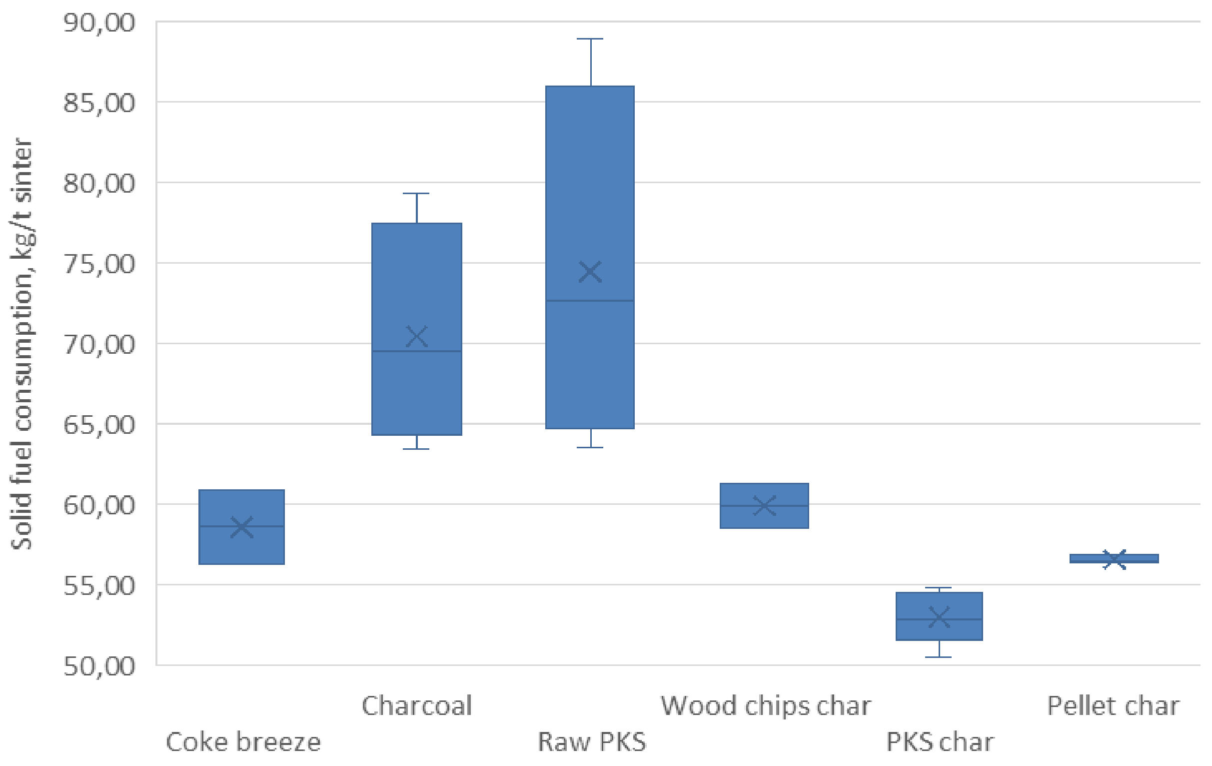
Pellet char



Pellet char slightly reduces solid fuel consumption and can be applied at replacement rates of up to 35%

Results about biochar application in sintering process

SOLID FUEL CONSUMPTION

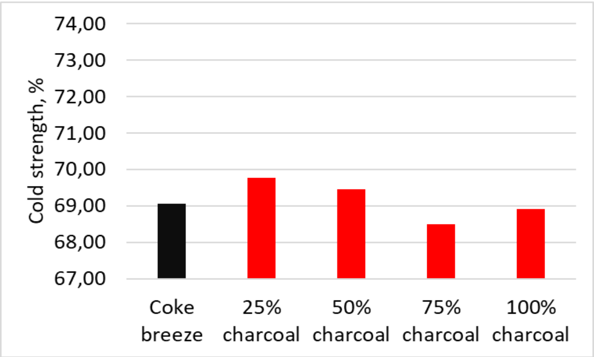


Solid fuel consumption increases markedly when coke breeze is replaced with charcoal or raw PKS, whereas PKS char and pellet char reduce fuel demand below the coke-breeze baseline, with wood-chips char showing only a slight increase.

Results about biochar application in sintering process

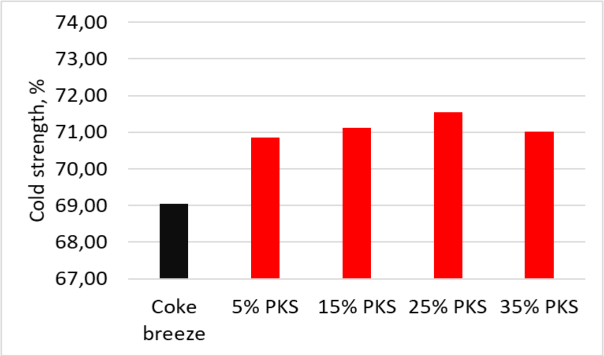
ISO T COLD STRENGTH

Charcoal



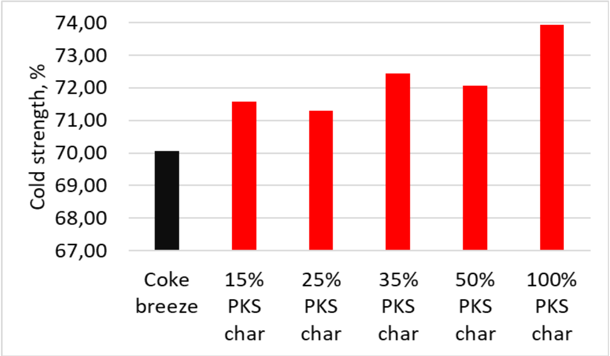
Charcoal substitution increases ISO T up to a 50% replacement level; higher substitution decreases ISO T to values below or similar to those of coke breeze

Raw PKS



Increasing raw PKS substitution enhances ISO T, yielding strengths consistently above those of coke breeze

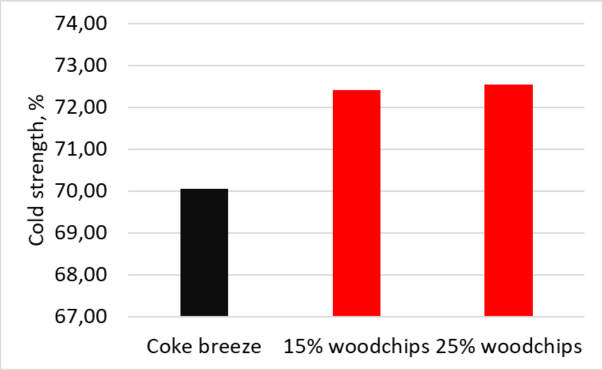
PKS char



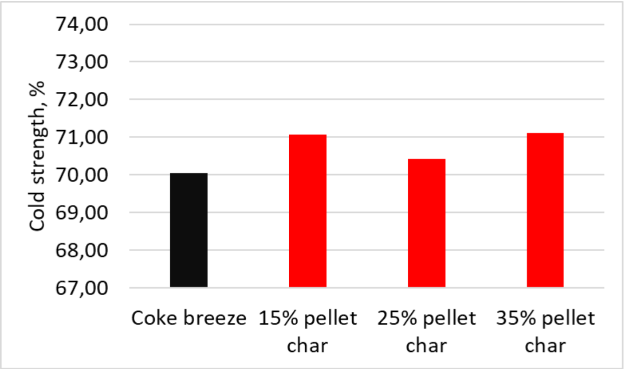
ISO T rises with higher PKS char substitution and remains superior to the coke-breeze benchmark

Wood chips char

Wood-chips char substitution results in ISO T values exceeding those of coke breeze



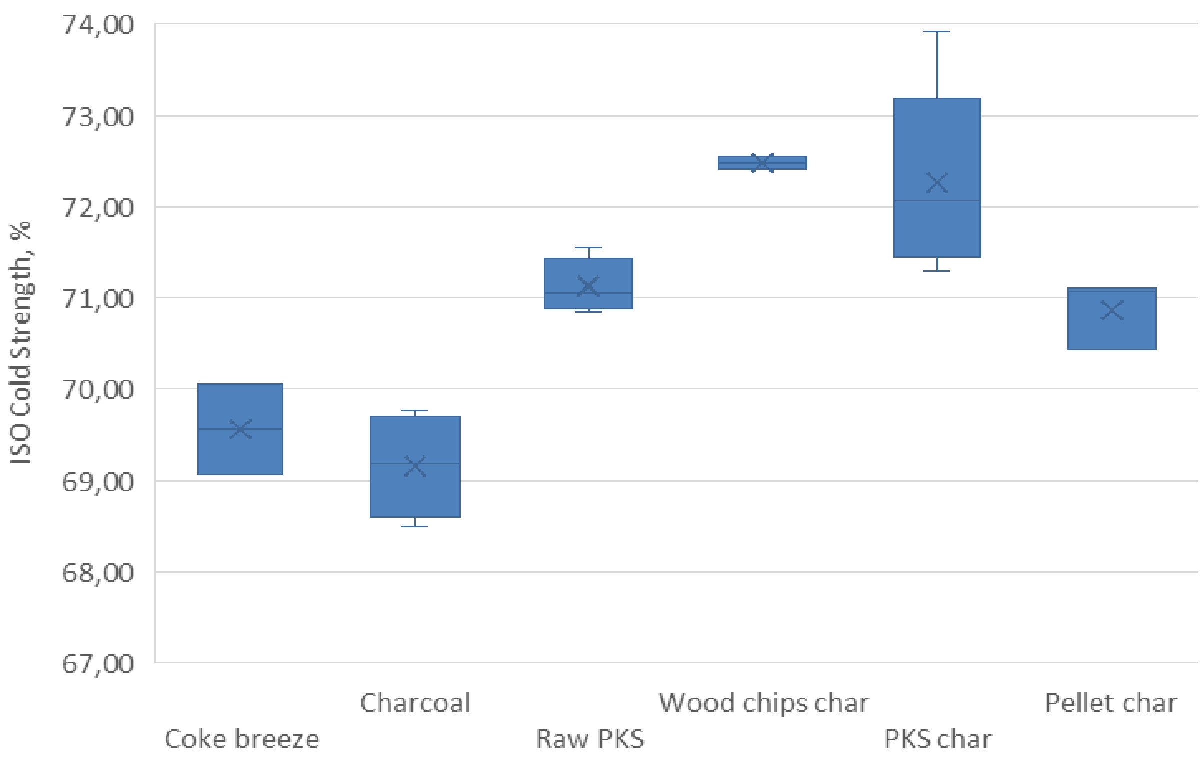
Pellet char



Pellet char improves cold strength up to a 35% substitution level

Results about biochar application in sintering process

ISO T COLD STRENGTH

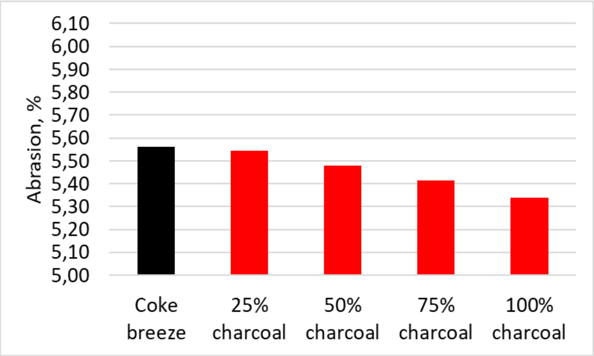


The ISO cold strength improves with all alternative fuels compared to coke breeze, with wood-chips char and PKS char showing the highest values, while charcoal and pellet char provide moderate yet still enhanced strength

Results about biochar application in sintering process

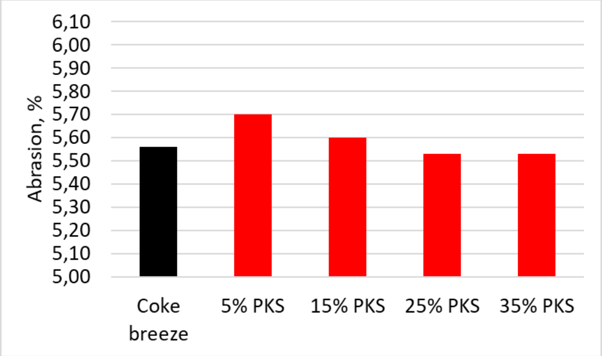
ISO A ABRASION

Charcoal



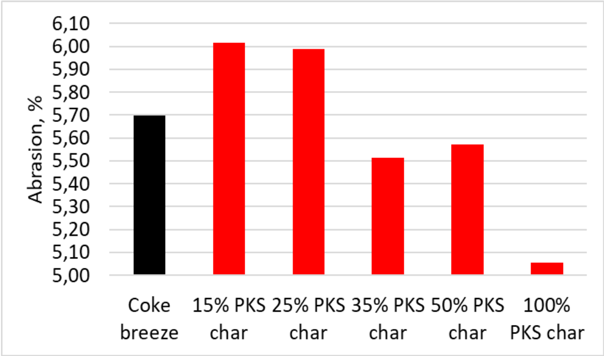
Increasing charcoal substitution reduces abrasion, yielding values lower than those of coke breeze

Raw PKS



At 15% raw PKS substitution, abrasion exceeds that of coke breeze, whereas at 25% and 35% it falls below the coke-breeze reference

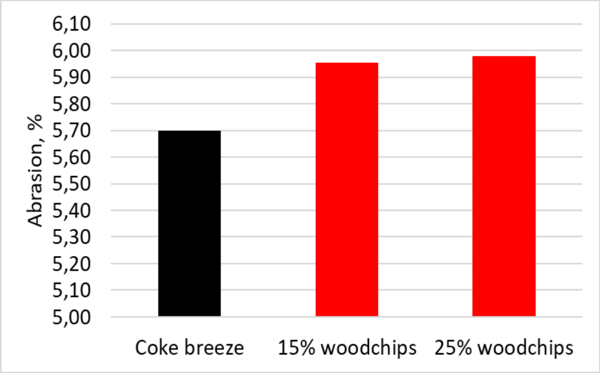
PKS char



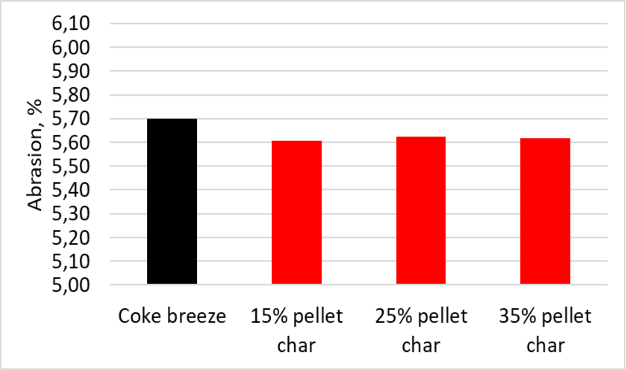
PKS char increases abrasion up to a 25% substitution level, but at 35% the abrasion becomes lower than for coke breeze

Wood chips char

Wood-chips char substitution initially results in abrasion values higher than those of coke breeze



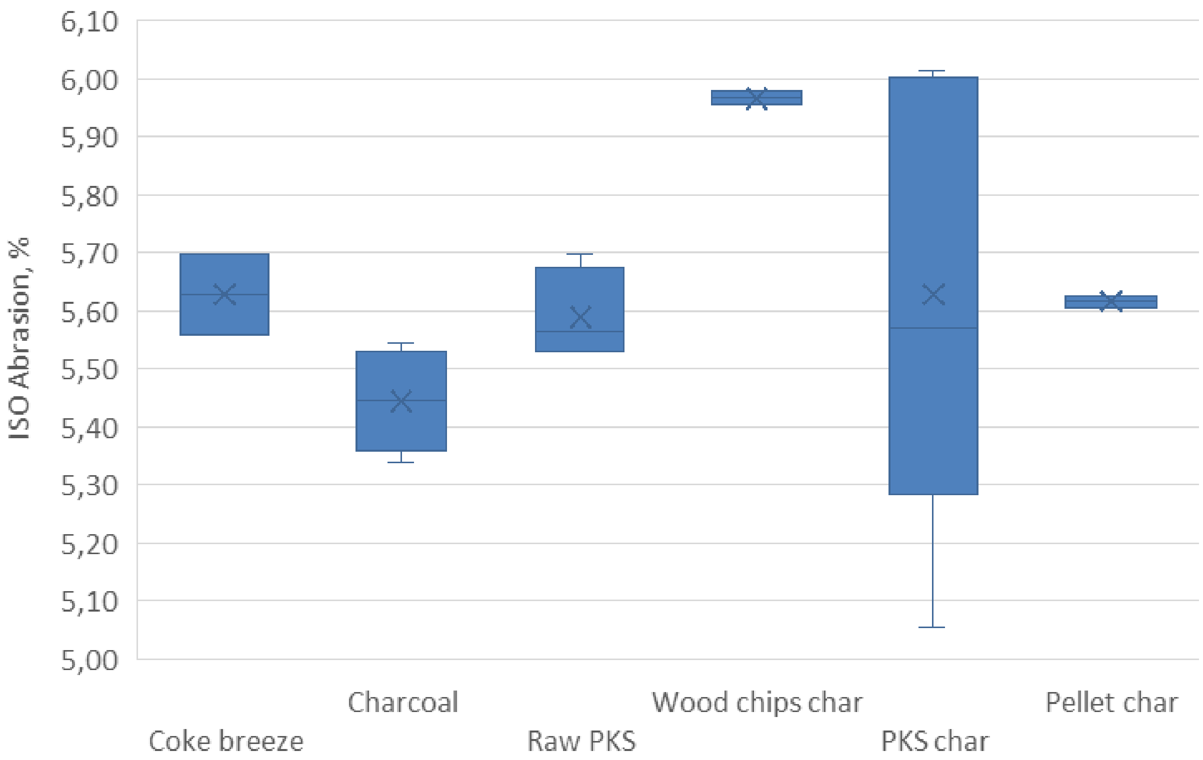
Pellet char



Pellet char produces abrasion values lower than those of coke breeze

Results about biochar application in sintering process

ISO A ABRASION

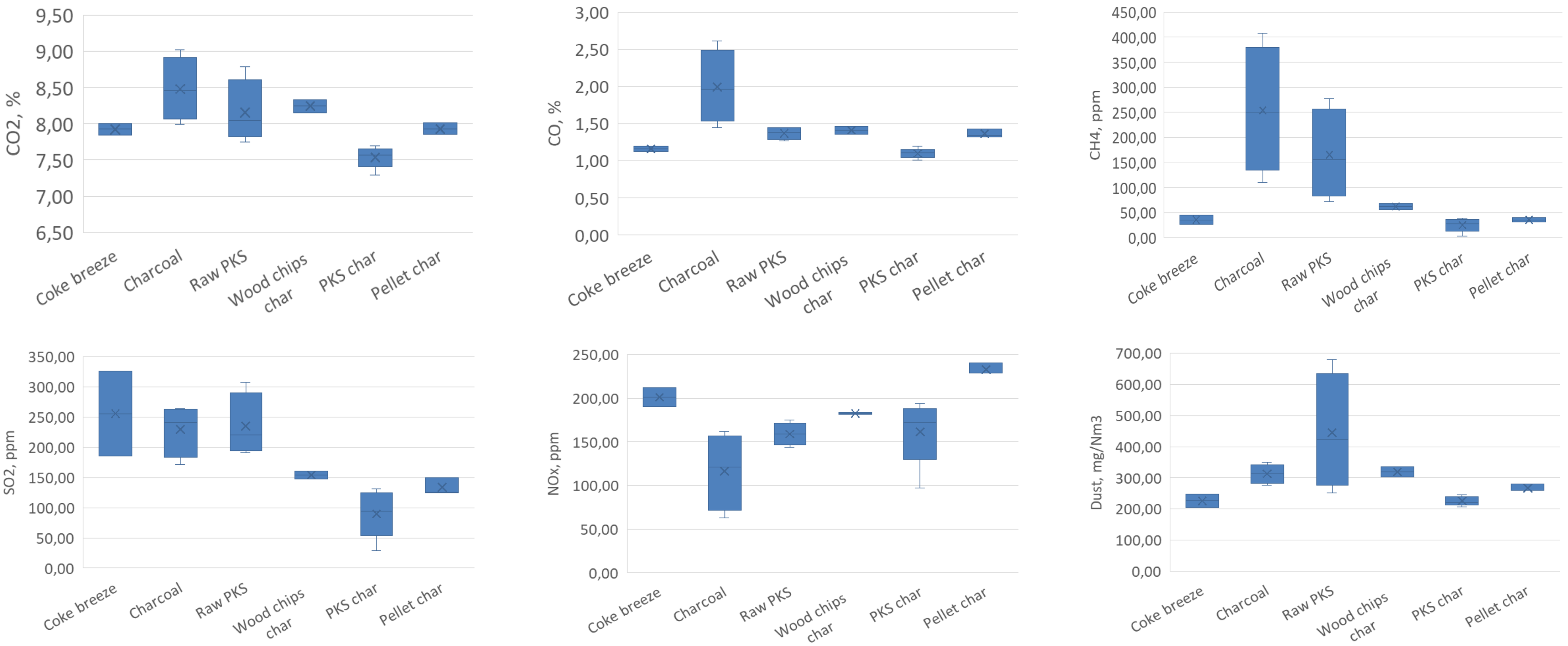


Abrasion varies across the alternative fuels: charcoal shows the lowest abrasion, comparable to or better than coke breeze, while raw PKS and wood-chips char exhibit slightly higher values. PKS char demonstrates the highest abrasion variability, whereas pellet char remains close to the coke-breeze baseline.

Results about biochar application in sintering process

CONTENT IN OFF GASES

Before gas cleaning system

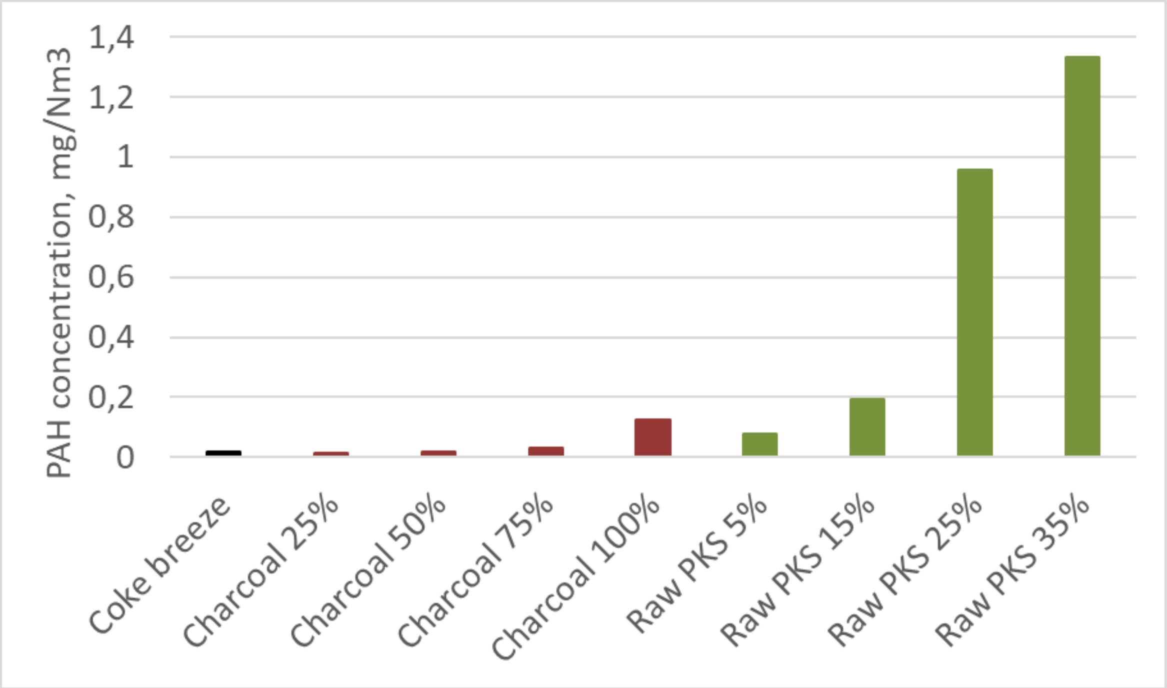


Across all measured pollutants, charcoal and raw PKS generate higher CO_2, CO, CH_4, and dust emissions than coke breeze, whereas PKS char and pellet char consistently produce the lowest levels of gaseous and particulate pollutants. SO_2 and NO_x emissions decrease for most biomass-derived fuels, indicating cleaner sulfur and nitrogen combustion pathways, with the exception of moderate NO_x increases observed for some materials.

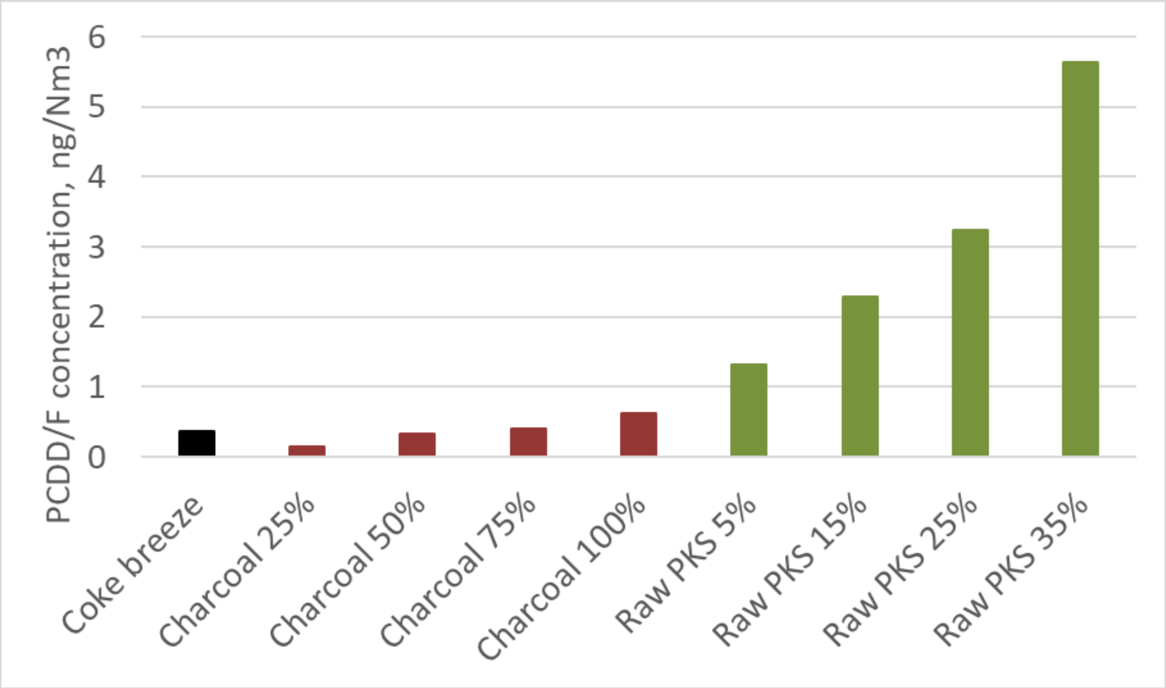
Results about biochar application in sintering process

CONTENT IN OFF GASES

Before gas cleaning system



PAH emissions remain low and comparable to coke breeze for all charcoal substitution levels, whereas raw PKS shows a strong increase in PAH concentration at higher replacement ratios, indicating that untreated biomass significantly enhances PAH formation.



PCDD/F emissions stay at low levels for charcoal-based substitution, while raw PKS leads to a substantial rise in dioxin and furan concentrations with increasing replacement ratios.

PAH and PCDD/F analyses for the rest of the alternative fuels are in progress

CONCLUSIONS

- **Productivity**: Charcoal and both raw and charred PKS show the highest productivity (≈40 t/m²/day), outperforming coke breeze; pellet char is slightly lower but still better, while wood-chip char performs worse.
- **Solid fuel consumption**: Raw PKS and charcoal increase consumption due to lower carbon content, whereas PKS char and pellet char reduce it.
- **Mechanical behaviour**: Charcoal, raw PKS, PKS char, and wood-chip char generally improve ISO T, while pellet char enhances cold strength at moderate substitution. Abrasion trends are material-dependent: charcoal reduces abrasion, raw PKS and PKS char shift from higher to lower abrasion with increased substitution, and wood-chip char shows inconsistent effects.
- **Gaseous emissions**: Charcoal and raw PKS increase CO_2, CO, and CH_4, whereas PKS char and pellet char substantially reduce gaseous pollutants. SO_2 and NO_x typically decrease with biomass fuels; pellet char yields the lowest dust emissions.
- **Toxic organic emissions**: PAH and PCDD/F remain low for charcoal but rise sharply with higher raw PKS substitution, showing strong fuel-type dependence.

There is a possibility of fully (100%) substituting coke breeze with charcoal and PKS char, with the PKS char exhibiting the most beneficial effect on process productivity, fuel consumption, sinter strength, and emissions.

Material Characterization – phase Analysis Of Sinters

Results about biochar application in sintering process

MATERIAL FOR TESTING

Coke breeze	Coke breeze + % charcoal from hardwood	Coke breeze + % palm kernel shell (Raw PKS)
100 %	25 %	5 %
	50 %	15 %
	75 %	25 %
	100 %	

Results about biochar application in sintering process

METHODOLOGY

X-Ray diffraction

- Qualitative phase analysis
- Quantitative phase analysis – Rietveld's method

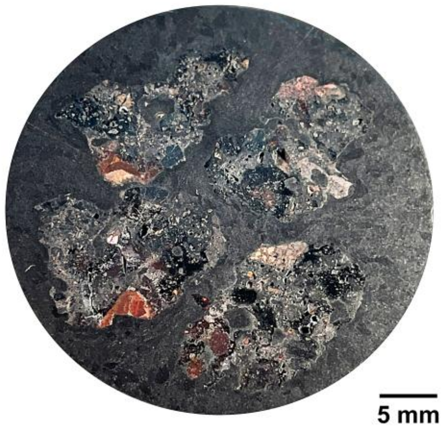
Scanning Electron Microscopy

- Microstructure observation
- Chemical analysis in micro-areas

Samples of sinters for diffraction tests were crushed to a grain size of less than 10 μm.

The sample for quantitative phase analysis was prepared as a mixture of a known amount of sample supplied and powdered corundum.

For microscopic examination the sinter grains were embedded in a conductive resin without crushed.



Results about biochar application in sintering process

An amorphous component in a sintered material is a phase that does not have a regular, crystalline

Significance of the amorphous component

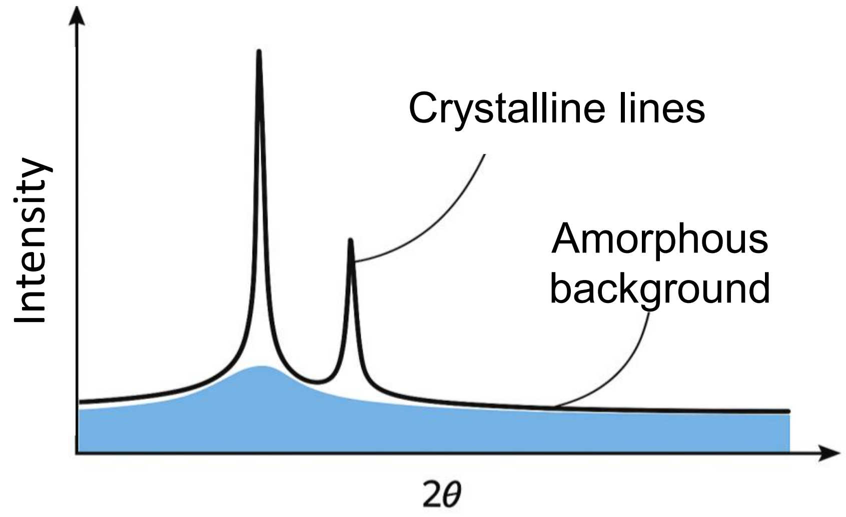
Positive effects

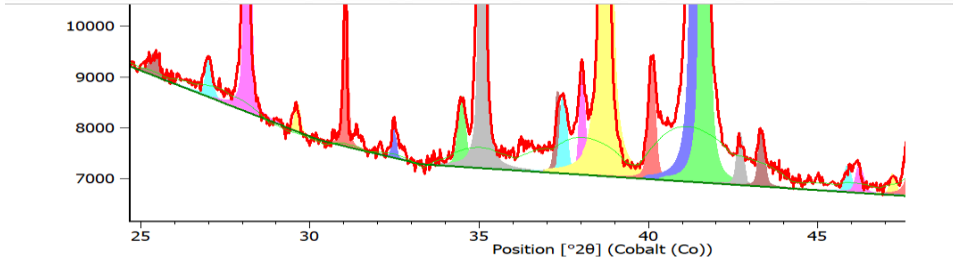
- Increases density and tightness of the sinter
- Improves chemical resistance
- Acts as a binding phase between crystalline grains
- Can enhance sinterability (lowers sintering temp)

Negative effects

- May reduce hardness or strength at high temperatures
- Is often less thermally stable
- Can cause creep or deformation during long-term exposure

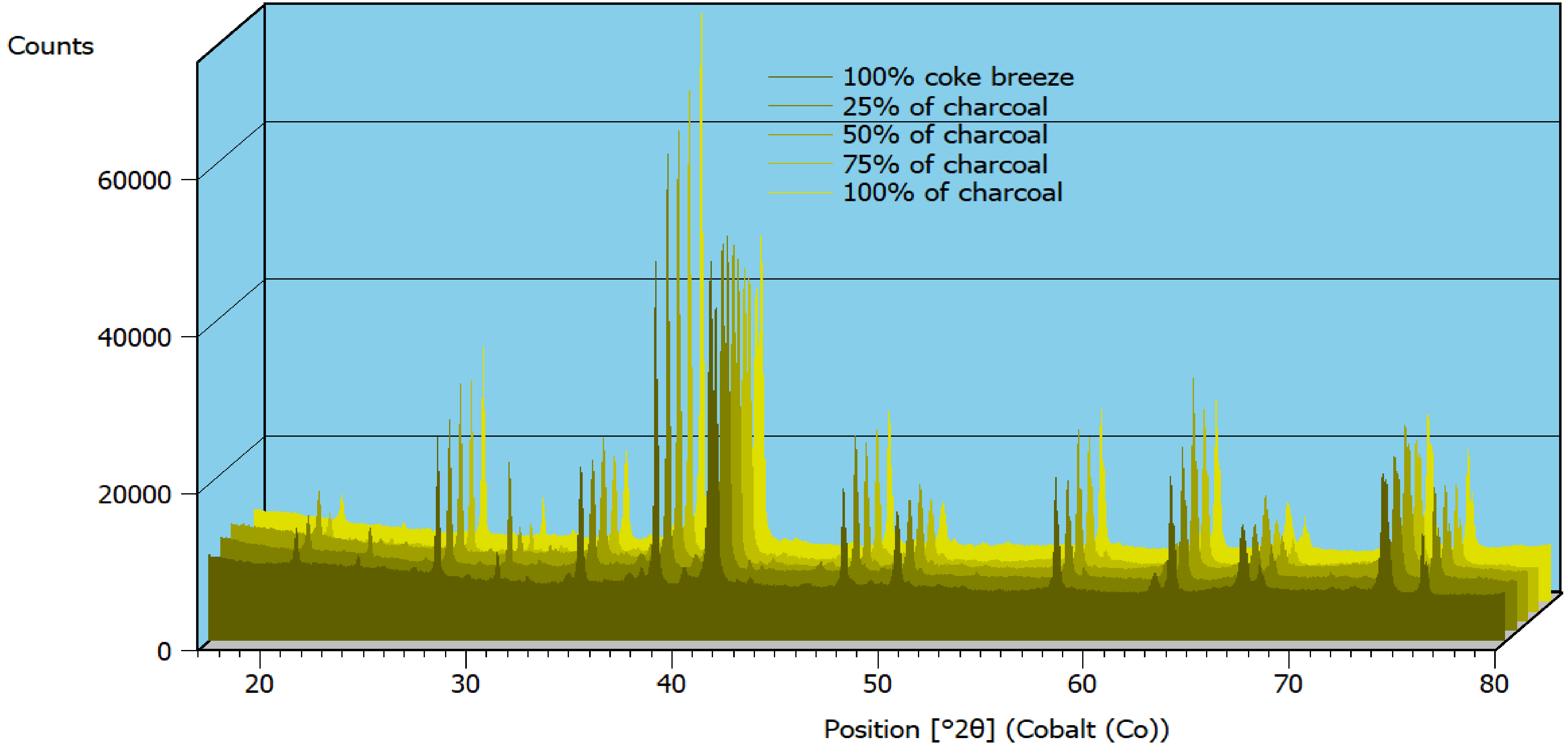
$$X_{amorph} = 100\% - X_{cryst}$$





Results about biochar application in sintering process

Results of qualitative phase analysis – sinters with charcoal from hardwood



Comparison of diffraction patterns for sinters with different content of charcoal from hardwood
The same diffraction lines for all sinters with different intensity, which affects the volume fraction of individual phases

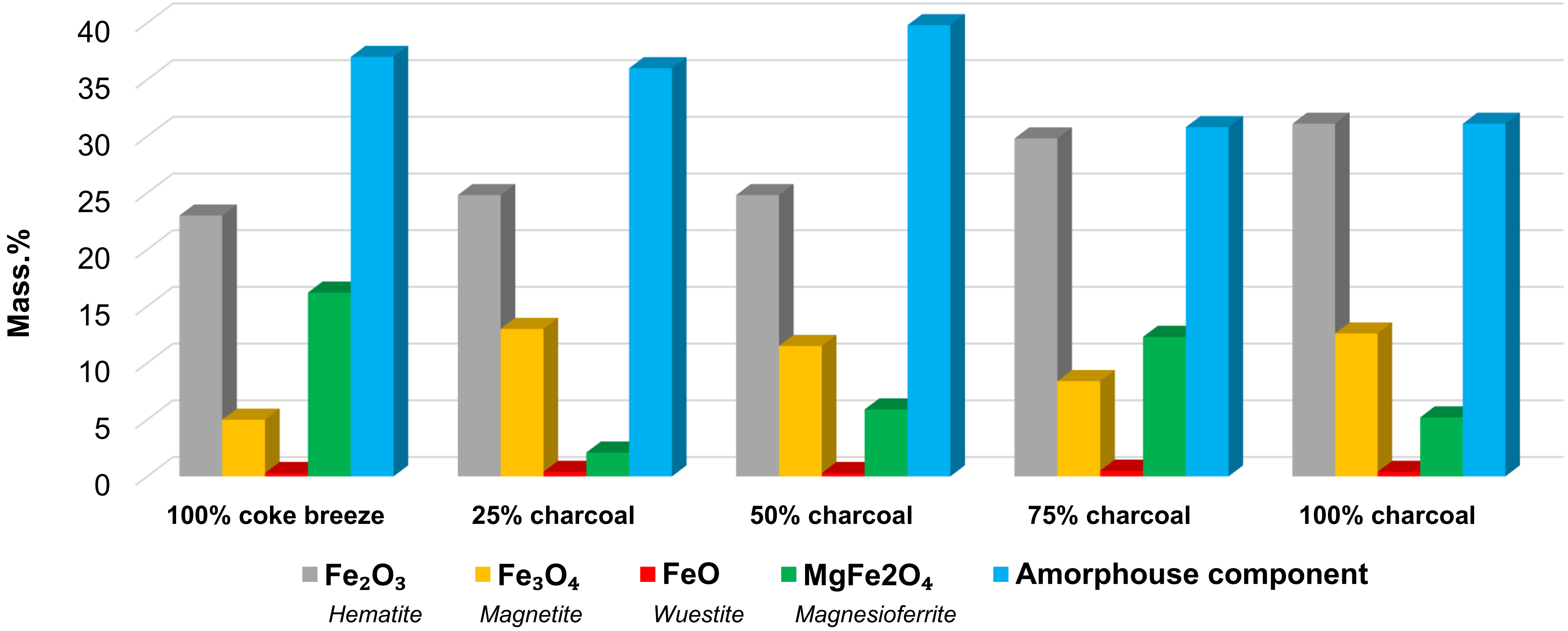
Results about biochar application in sintering process

Results of quantitative phase analysis – sinters with charcoal from hardwood

Phase		Sinter, mass. %				
		Coke breeze	Charcoal from hardwood			
Mineral name	**Chemical formula**	**100%**	**25%**	**50%**	**75%**	**100%**
Hematite	Fe_2O_3	23.0	24.8	24.8	29.8	31.1
Magnetite	Fe_3O_4	5.0	13.0	11.5	8.4	12.6
Wuestite	FeO	0.3	0.4	0.3	0.5	0.4
Magnesioferrite	$MgFe_2O_4$	16.2	2.1	5.9	12.3	5.2
Larnite	β-Ca_2SiO_4	7.8	7.0	6.3	8.0	10.3
Calcio-olivine	Ca_2SiO_4	1.7	2.8	4.7	2.3	1.7
Wollastonite	$CaSiO_3$	2.5	1.0	1.9	0.4	0.2
Rankinite	$Ca_3Si_2O_3$	1.7	-	1.4	1.1	4.0
Diopside	$CaMgFeSi_2O_6$	-	4.1	-	-	-
Hedenbergite	$CaAlFeMgFeSi_2O_6$	1.8	2.0	1.3	3.4	1.4
Quartz	SiO_2	1.2	5.0	1.0	1.5	1.4
Periglase	MgO	3.0	2.0	1.9	1.0	0.6
Amorphouse content		37.0	36.0	39.8	30.8	31.1

Results about biochar application in sintering process

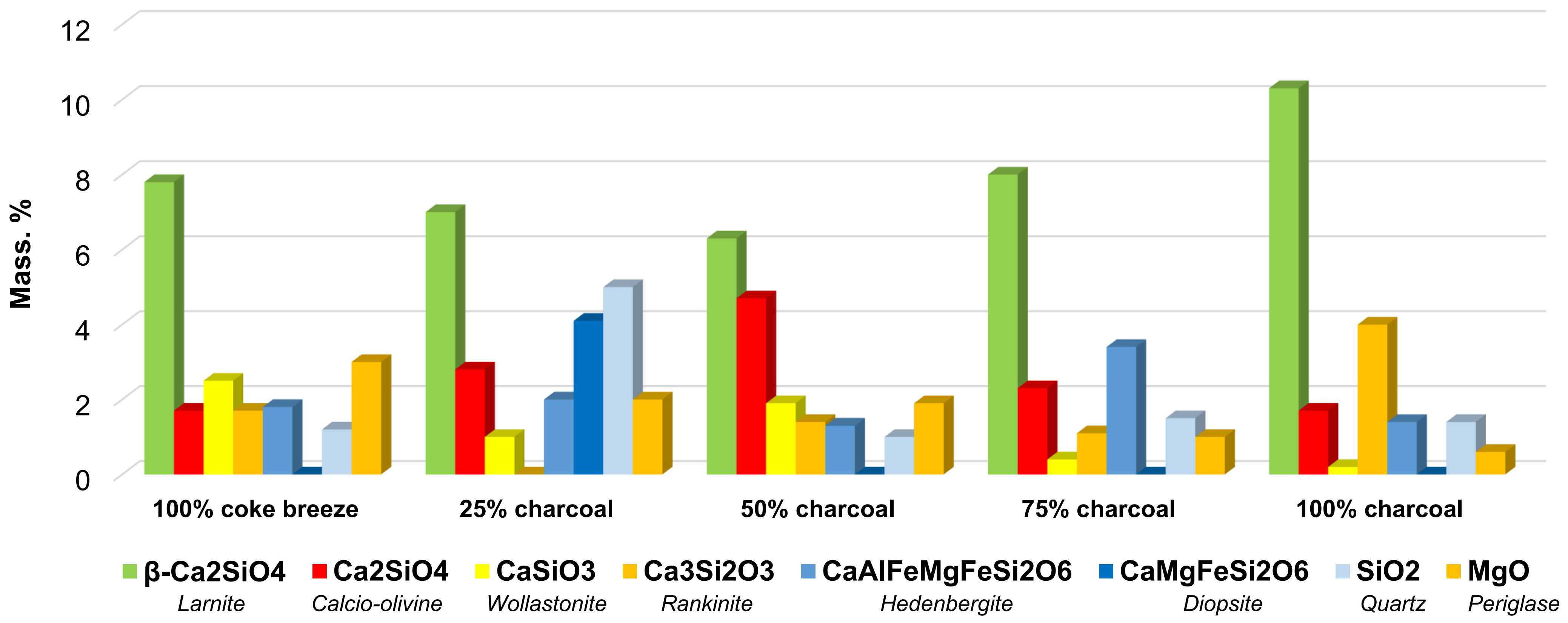
Results of quantitative phase analysis – sinters with charcoal from hardwood



The amount of iron oxides and amorpouse content in sinters depending on the percentage of charcoal from hardwood, mass.%

Results about biochar application in sintering process

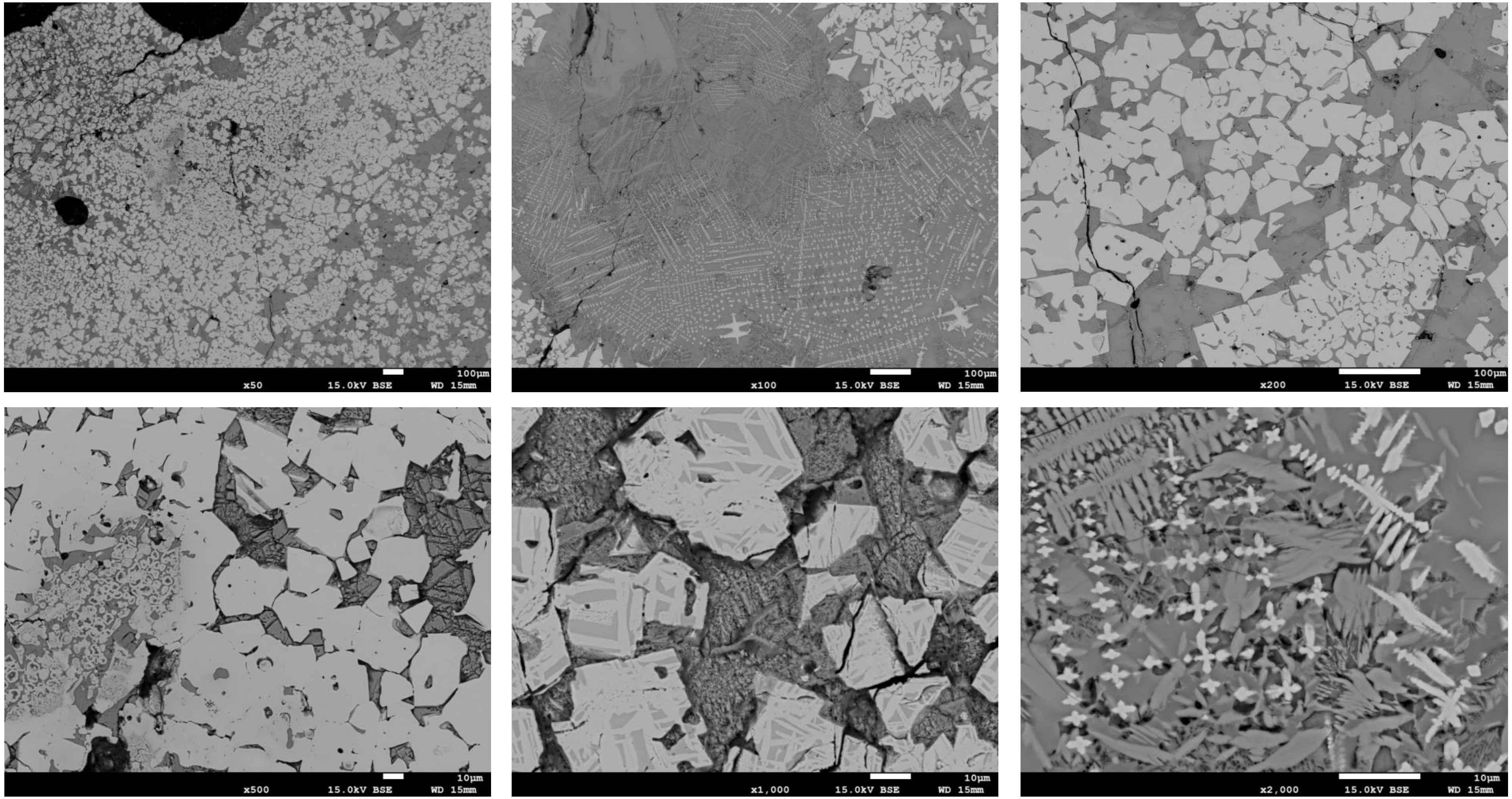
Results of quantitative phase analysis – sinters with charcoal from hardwood



The amount of other phases in sinters depending on the percentage of charcoal from hardwood, mass.%

Results about biochar application in sintering process

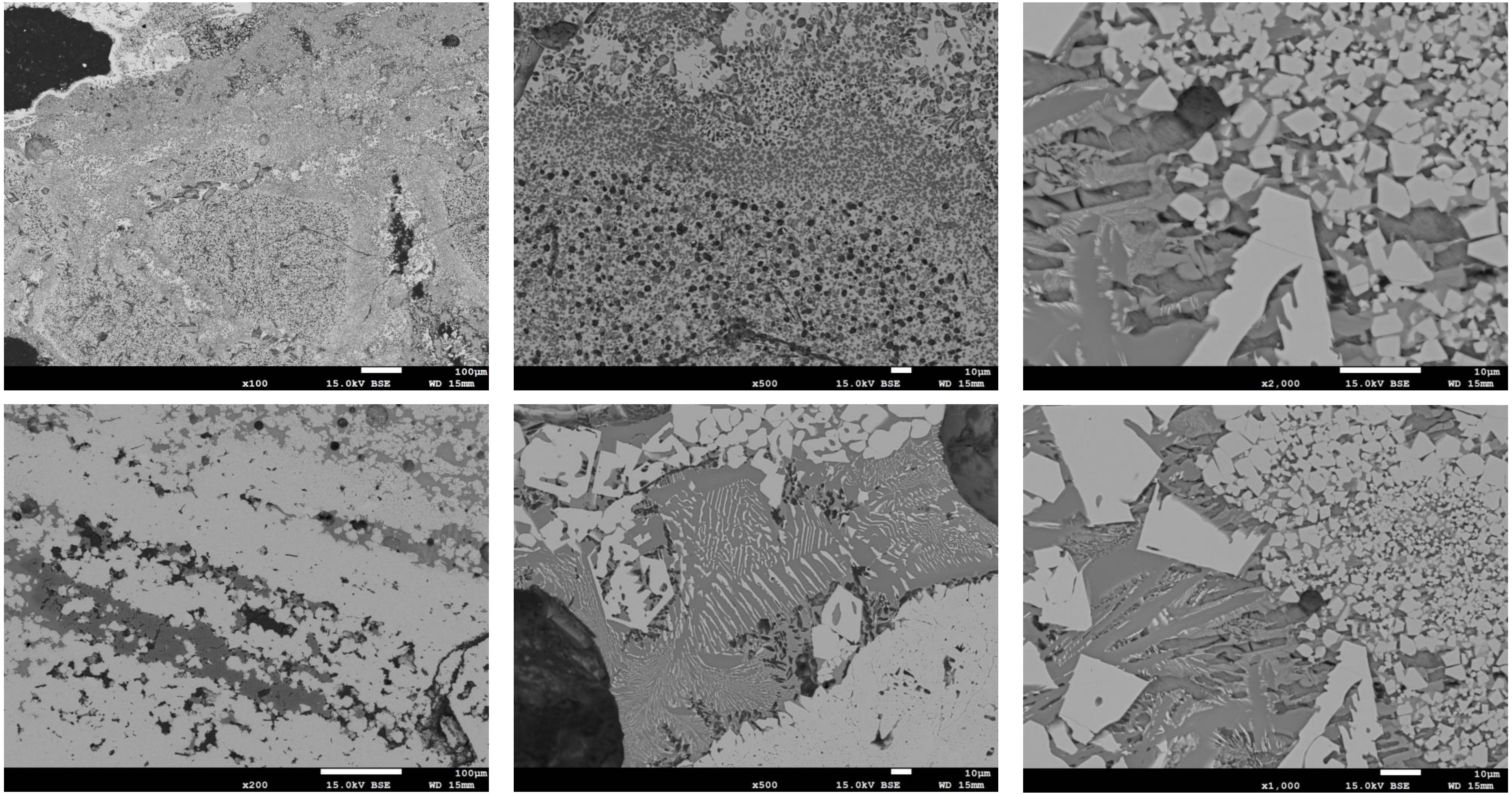
Results of microstructure analysis – sinter with 100% coke breeze



Differences in the morphology of phase components with high heterogeneity of sinter's lumps

Results about biochar application in sintering process

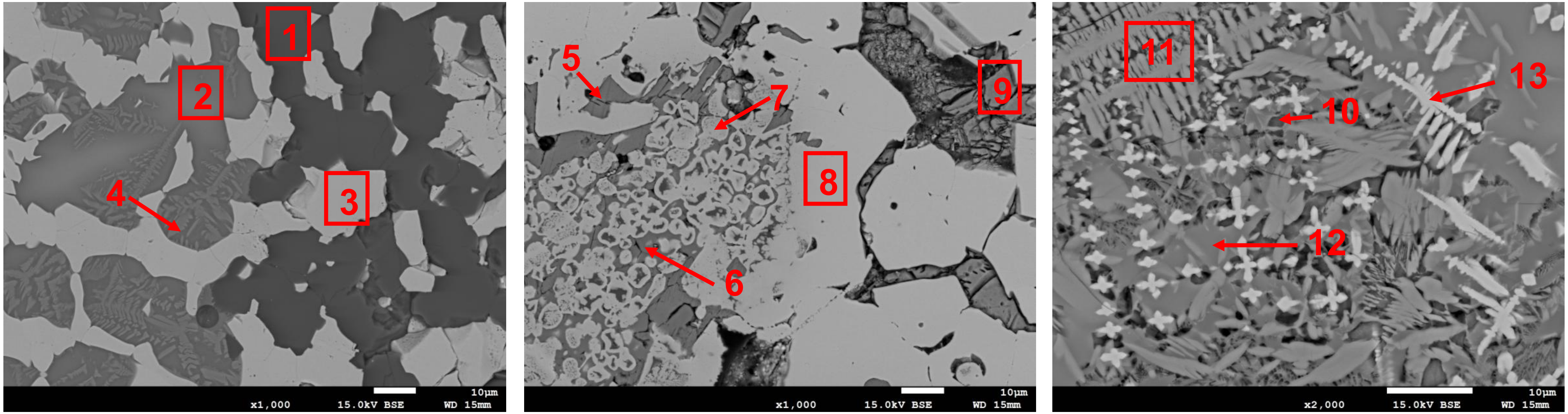
Microstructure results – sinter with 25% of charcoal from hardwood



Differences in the morphology of phase components with high heterogeneity of sinter's lumps

Results about biochar application in sintering process

Results of SEM-EDS analysis – sinter with 100% coke breeze

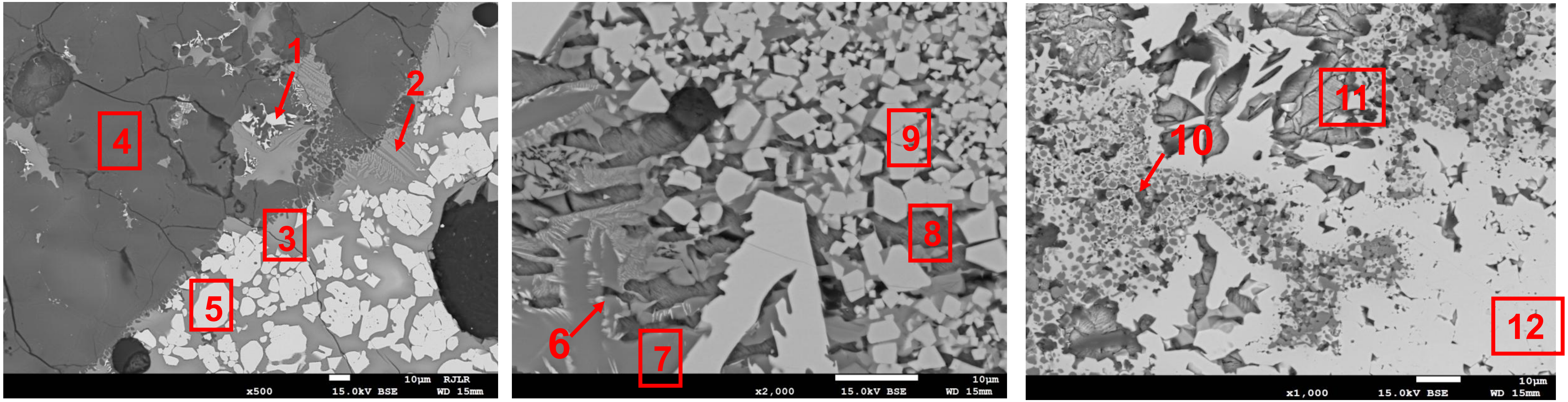


Element	The concentration of elements in selected micro-areas [wt%]												
	1	2	3	4	5	6	7	8	9	10	11	12	13
O	51.9	44.4	28.6	38.3	37.5	39.5	30.4	37.3	28.6	22.5	36.1	38.1	29.2
Mg	-	1.2	-	1.9	7.4	12.2	10.9	3.1	5.3		0.4		0.7
Al	-	1.3	-	1.1	-	-	-	-	0.7	0.8	1.0	0.7	0.5
Si	48.1	22.4	-	22.3	15.7	15.1	-	15.4	-	17.6	12.8	16.5	2.3
Ca	-	19.4	-	17.9	37.9	28.4	-	41.8	0.9	46.7	20.2	29.8	4.8
Fe	-	11.4	71.4	18.5	1.6	4.8	58.7	2.4	64.5	12.5	27.8	14.9	62.5

SEM-BSE images with marked places where the chemical composition analysis was performed along with the weight content of individual elements

Results about biochar application in sintering process

Results of SEM-EDS analysis – sinter with 25% of charcoal from hardwood

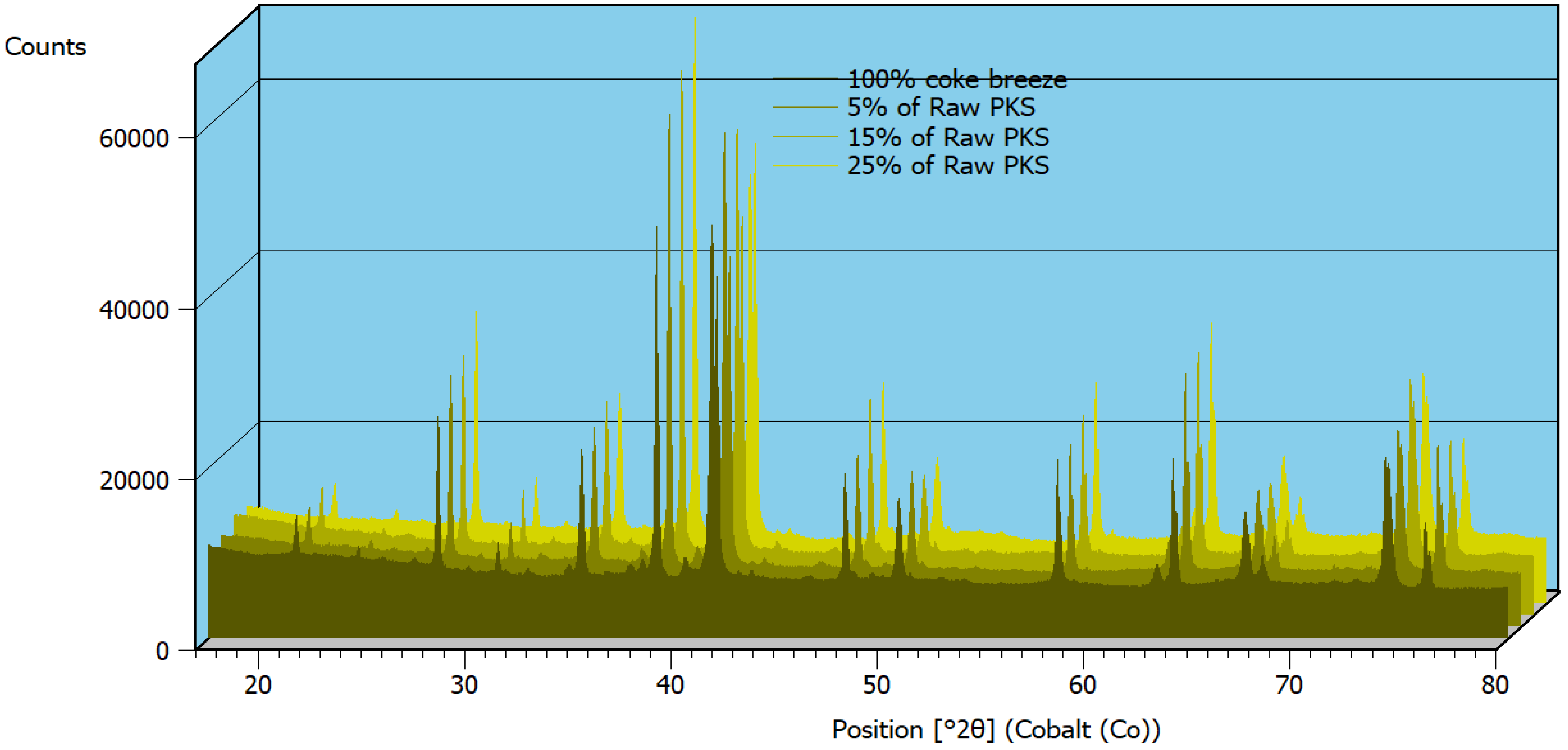


Element	The concentration of elements in selected micro-areas [wt%]											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
O	31.4	38.4	41.8	53.4	29.5	35.4	40.8	35.9	29.1	36.1	3.5	28.8
Mg	-	1.6	0.6	-	-	2.2	0.8	0.5	4.9	52.6	-	6.4
Al	0.2	0.6	0.9	-	0.2	1.2	0.7	0.4	0.5	-	-	0.4
Si	1.3	19.9	23.5	46.6	0.1	9.6	21.3	17.5	-	-	15.3	-
Ca	-	17.2	20.2	-	-	13.3	32.4	42.8	1.0	1.4	47.2	1.6
Fe	67.0	22.3	13.1	-	68.8	38.3	3.9	2.8	64.6	9.9	-	62.8

SEM-BSE images with marked places where the chemical composition analysis was performed along with the weight content of individual elements

Results about biochar application in sintering process

Results of qualitative phase analysis – sinters with raw PKS (palm kernel shell)



Comparison of diffraction patterns for sinters with different content of charcoal from hardwood
The same diffraction lines for all sinters with different intensity, which affects the volume fraction of individual phases

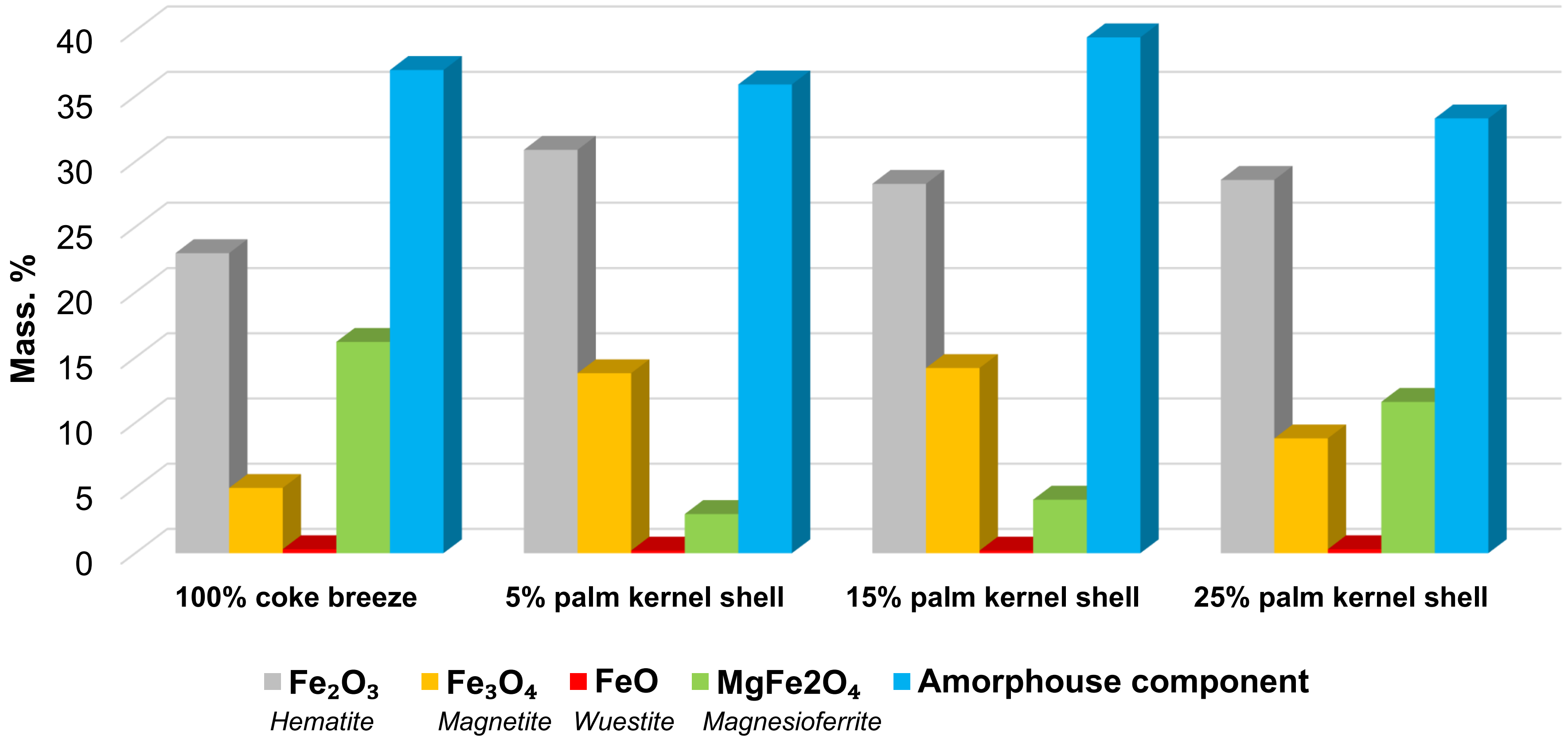
Results about biochar application in sintering process

Results of quantitative phase analysis – sinters with raw PKS (palm kernel shell)

Phase		Sinter, mass. %			
		Coke breeze	Raw PKS (palm kernel shell)		
Mineral name	**Chemical formula**	**100%**	**5%**	**15%**	**25%**
Hematite	Fe_2O_3	23.0	30.9	28.3	28.6
Magnetite	Fe_3O_4	5.0	13.8	14.2	8.8
Wuestite	FeO	0.3	0.2	0.2	0.3
Magnesioferrite	$MgFe_2O_4$	16.2	3.0	4.1	11.6
Larnite	β-Ca_2SiO_4	7.8	8.0	6.3	6.7
Calcio-olivine	Ca_2SiO_4	1.7	1.0	1.0	1.3
Wollastonite	$CaSiO_3$	2.5	1.5	0.8	1.3
Rankinite	$Ca_3Si_2O_3$	1.7	-		-
Diopside	$CaMgFeSi_2O_6$	-	1.8	2.1	2.6
Hedenbergite	$CaAlFeMgFeSi_2O_6$	1.8	0.3	0.2	0.4
Quartz	SiO_2	1.2	2.0	1.5	2.3
Periglase	MgO	3.0	2.0	1.0	-
Amorphouse content		37.0	35.9	39.5	33.3

Results about biochar application in sintering process

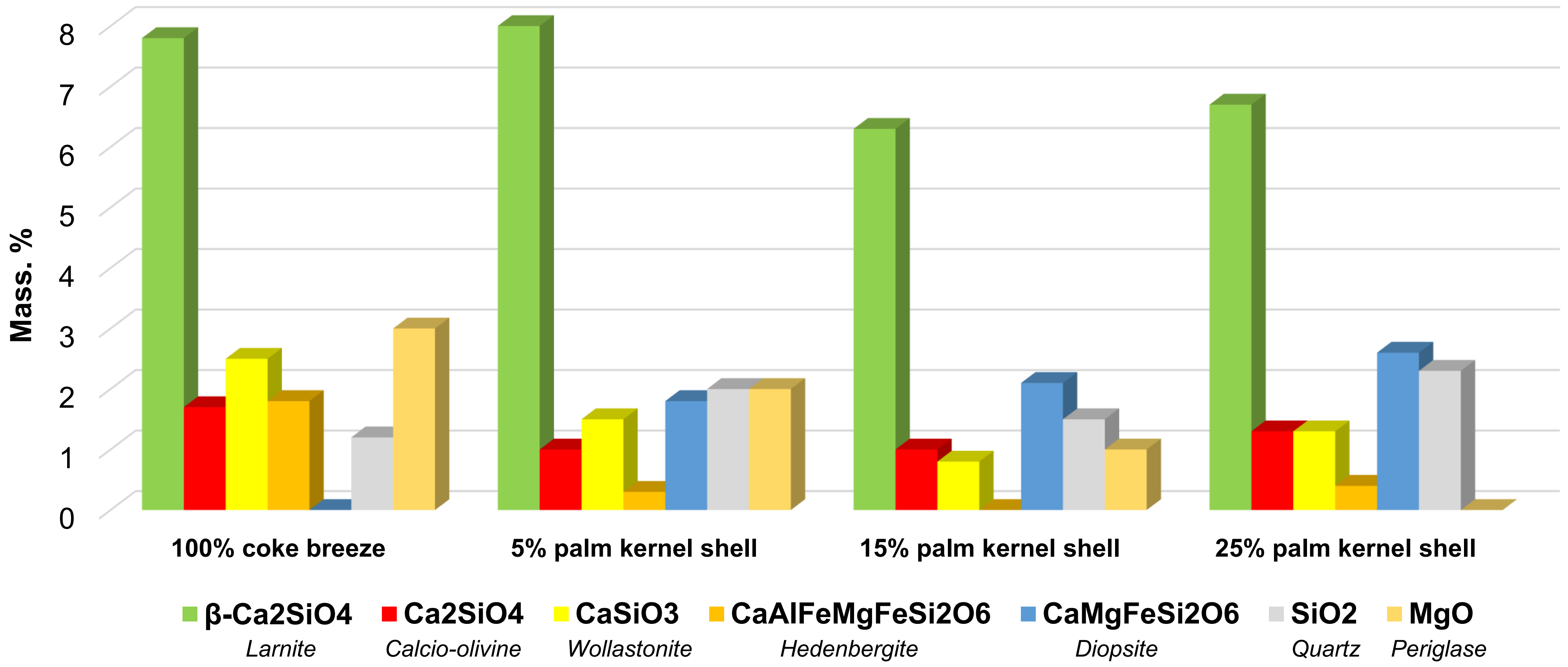
Results of quantitative phase analysis – sinters with raw PKS (palm kernel shell)



The amount of iron oxides and amorpouse content in sinters depending on the percentage of Raw PKS, mass. %

Results about biochar application in sintering process

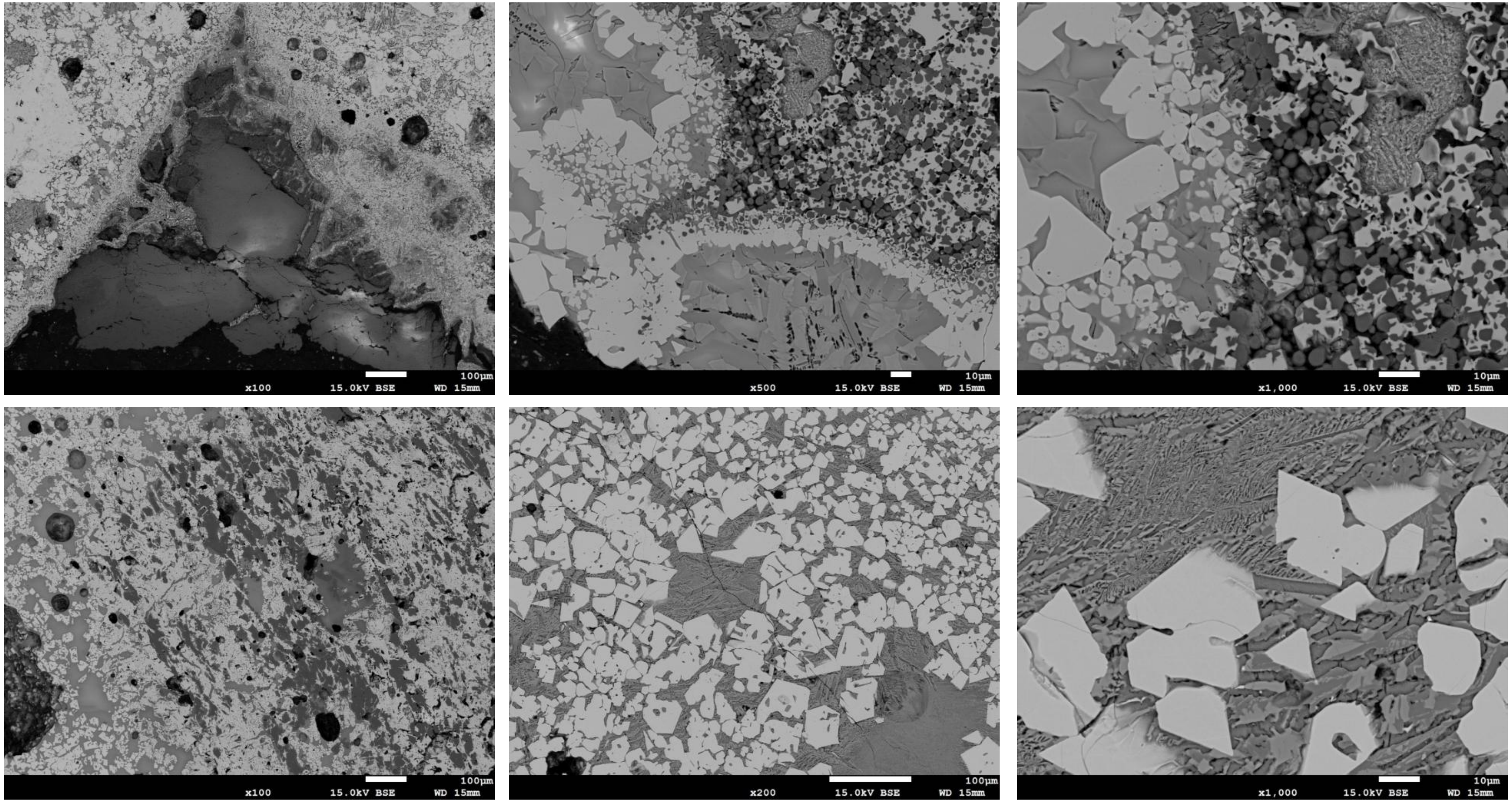
Results of quantitative phase analysis – sinters with raw PKS (palm kernel shell)



The amount of other phases in sinters depending on the percentage of Raw PKS, mass.%

Results about biochar application in sintering process

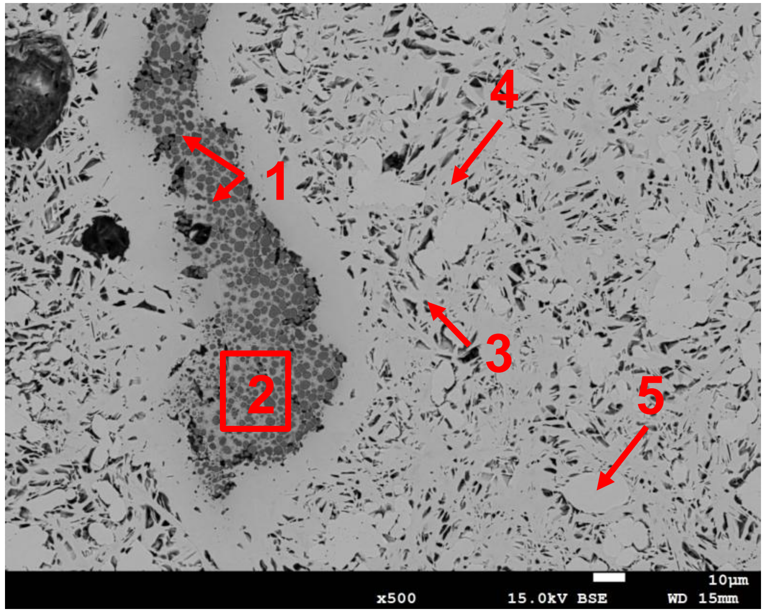
Microstructure results – sinters with 5% Raw PKS

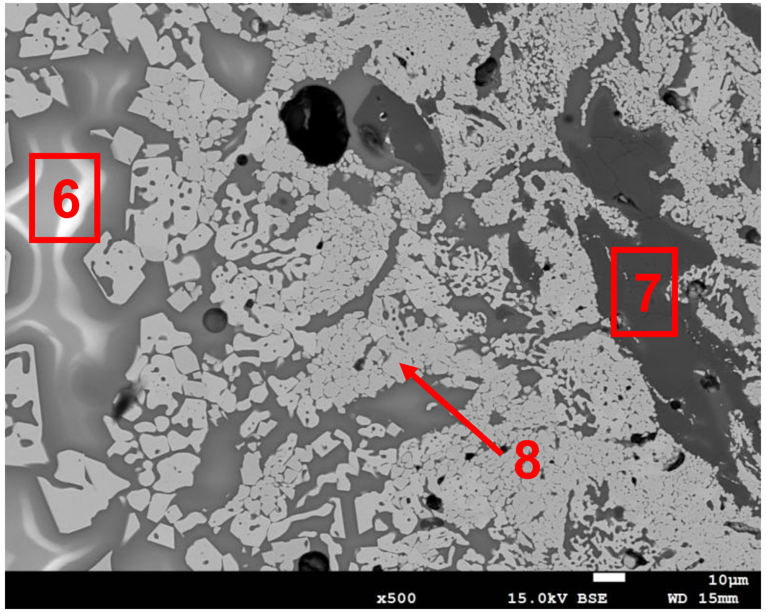


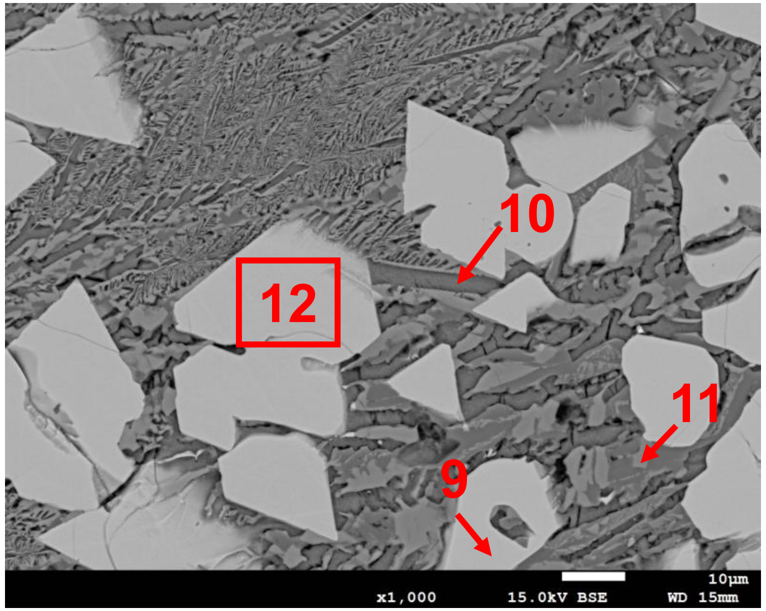
Differences in the morphology of phase components with high heterogeneity of sinter's lumps

Results about biochar application in sintering process

Results of SEM-EDS analysis – sinters with Raw PKS, 5% biomass





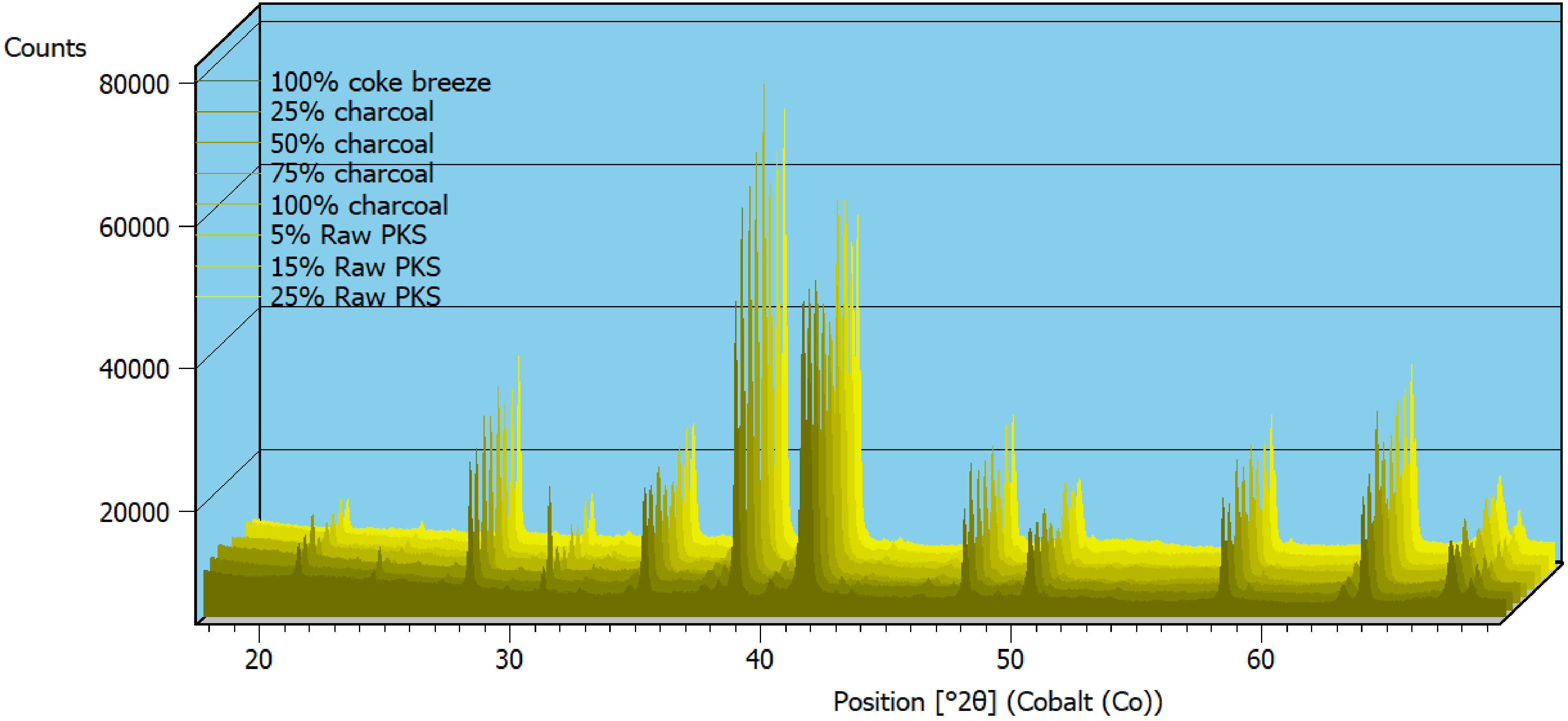


Element	The concentration of elements in selected micro-areas [wt%]											
	1	2	3	4	5	6	7	8	9	10	11	12
O	34.7	34.0	19.6	30.4	29.3	52.9	52.7	29.3	36.6	36.9	38.1	27.5
Mg	51.0	29.4	-	0.9	-	-	-	-	0.6	-	-	0.5
Al	-	-	-	0.6	-	3.7	-	-	2.1	0.3	2.1	0.5
Si	-	0.5	3.3	1.9	-	21.4	47.3	-	15.2	16.5	20.1	-
Ca	-	11.2	25.6	12.9	-	15.2	-	-	19.6	44.5	33.2	0.7
Fe	14.3	24.8	51.5	53.3	70.7	6.9	-	70.7	25.9	1.9	6.5	70.8

SEM-BSE images with marked places where the chemical composition analysis was performed along with the weight content of individual elements

Results about biochar application in sintering process

Results of qualitative phase analysis – comparision of all types of sinters



Comparison of diffraction patterns for sinters with different content of charcoal from hardwood
The same diffraction lines for all sinters with different intensity, which affects the volume fraction of individual phases

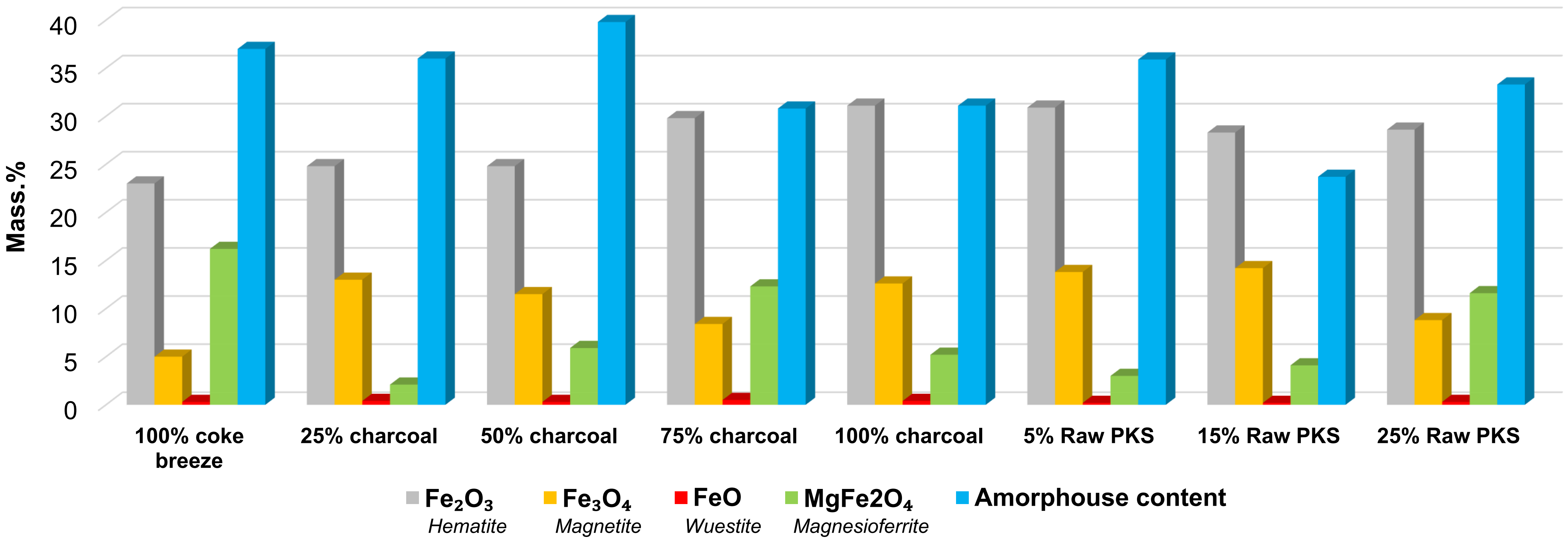
Results about biochar application in sintering process

Results of qualitative phase analysis – comparision of all sinters

Phase		Sinter, mass. %							
		Coke breeze	Charcoal from hardwood				Raw PKS (palm kernel shell)		
Mineral name	**Chemical formula**	**100%**	**25%**	**50%**	**75%**	**100%**	**5%**	**15%**	**25%**
Hematite	Fe_2O_3	23.0	24.8	24.8	29.8	31.1	30.9	28.3	28.6
Magnetite	Fe_3O_4	5.0	13.0	11.5	8.4	12.6	13.8	14.2	8.8
Wuestite	FeO	0.3	0.4	0.3	0.5	0.4	0.2	0.2	0.3
Magnesioferrite	$MgFe_2O_4$	16.2	2.1	5.9	12.3	5.2	3.0	4.1	11.6
Larnite	β-Ca_2SiO_4	7.8	7.0	6.3	8.0	10.3	8.0	6.3	6.7
Calcio-olivine	Ca_2SiO_4	1.7	2.8	4.7	2.3	1.7	1.0	1.0	1.3
Wollastonite	$CaSiO_3$	2.5	1.0	1.9	0.4	0.2	1.5	0.8	1.3
Rankinite	$Ca_3Si_2O_3$	1.7	-	1.4	1.1	4.0	-	-	-
Diopside	$CaMgFeSi_2O_6$	-	4.1	-	-	-	1.8	2.1	2.6
Hedenbergite	$CaAlFeMgFeSi_2O_6$	1.8	2.0	1.3	3.4	1.4	0.3	0.2	0.4
Quartz	SiO_2	1.2	5.0	1.0	1.5	1.4	2.0	1.5	2.3
Periglase	MgO	3.0	2.0	1.9	1.0	0.6	2.0	1.0	-
Amorphouse content		37.0	36.0	39.8	30.8	31.1	35.9	39.5	33.3

Results about biochar application in sintering process

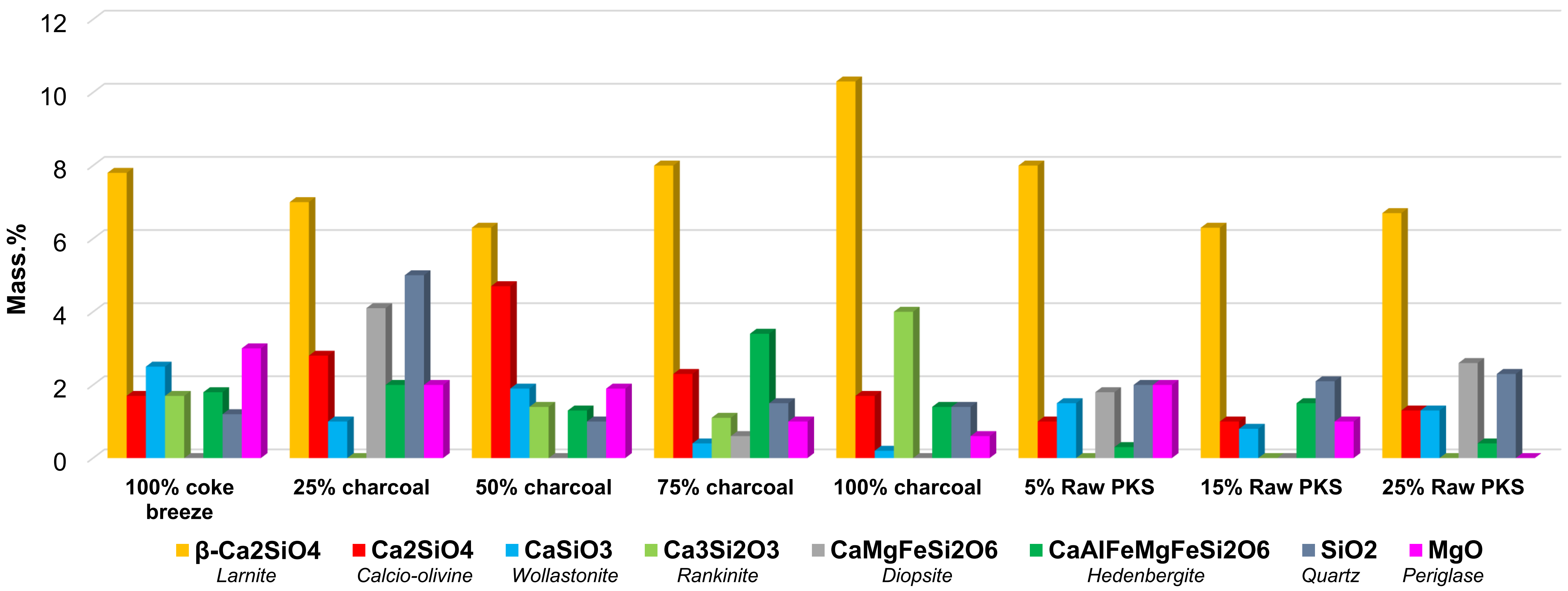
Results of qualitative phase analysis – comparison of all sinters



The amount of iron oxides and amorpouse content in all sinters, mass.%

Results about biochar application in sintering process

Results of qualitative phase analysis – comparison of all sinters



The amount of other phases in all sinters, mass.%

Conclusions

Regardless of the biomass added, sinters are characterized by similar, complex phase compositions. Differences occur in the content of individual phases within the sinter.

Adding biomass to the coke breeze significantly increases the proportion of hematite Fe_2O_3 and magnetite Fe_3O_4 in the sinters. A decrease in the magnesioferrite $MgFe_2O_4$ content is observed. The wüestite FeO content remains unchanged.

The total content of silicate phases ranges from 15 to 19%. The highest content of 19% occurs for sinter with 25% Raw palm kernel shell (PKS).

The presence of a silicate phase, rankinite, was observed in the sinters containing 100% Coke Breeze and charcoal, with the exception of the sinter containing 25% charcoal. In the PKS sinters, diopsite, which is formed by the decomposition of rankinite under high temperature, was observed. This suggests that a greater amount of heat was delivered to the sinters during the sintering process than in the case of sinters containing charcoal.

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