Cassava as an additive in biomass fuel pellet production

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Oscar Lockneus

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Handledare:
Sylvia Larsson
Robert Samuelsson

Sveriges lantbruksuniversitet
Institutionen för skogens biomaterial och teknologi
S-901 83 UMEÅ
www.slu.se/sbt
Tfn: 090-786 81 00
Rapport från Institutionen för skogens biomaterial och teknologi

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Supervisor: Sylvia Larsson, SLU, Department of Forest Biomaterials and Technology
Supervisor: Robert Samuelsson, SLU, Department of Forest Biomaterials and Technology
Examiner: Michael Finell, SLU, Department of Forest Biomaterials and Technology

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Abstract

In this study, the effects of using fine milled cassava stems as an additive in biofuel pellet production was compared to the effects of refined starch addition. The bulk biomass fuel raw material, to which the additive was added, was a blend of spruce and pine sawdust. An experimental design in the factors cassava/starch content, moisture content and material temperature was used. Measured responses were pellet bulk density, pellet durability, amount of fines, pelletizer motor current, pellet temperature, die temperature and CV for pelletizer motor current (a measure of process stability). Each response was modeled by multiple linear regression (MLR). Good models were found for pellet bulk density, pellet durability and amount of fines, verified by the model performance indicators R^2 and Q^2. The effects of cassava stem and starch addition showed strong similarities. Both additives have a weak positive effect on pellet bulk density. Both cassava and starch had positive effect on pellet durability, in particular at low moisture contents (MC) ~11 %. At ~14 % the effect of the cassava stems was less pronounced. The highest durability was achieved at low moisture content (11 % MC) when using cassava as an additive. Both additives have a negative effect on amount of fines. Consequently, results from this study show that cassava stems can be used as a substitute to refined starch for increasing fuel pellet durability.

Keywords: Durability, bulk density, fines, quality, harvest residues

Sammanfattning

I den här studien har effekten av att använda finmalda kassavastammar som bindemedel vid pelletering av biobränsle jämförts med effekten av raffinerad stärkelse. Biomassan var en 50/50 blandning av tall- och gran-spån, till vilken respektive additiv tillsattes, och pelleterades vid olika fukthalter och med olika tillsatser av ånga. Detta för att avgöra om denna raffinerade stärkelse skulle kunna ersättas av de stärkelserika skörderesterna från kassavaodlingar. Egenskaper efter pelletering som jämfördes var: bulkdensitet, hållfasthet, mängden finfraktioner, motorström, pellettemperatur, matristemperatur och CV för motorströmmen (ett mått på motorströmmens jämnhet). Resultatet blev att signifikanta modeller, för hur faktorerna påverkar de uppmätta egenskaperna, kunde byggas för parametrarna; bulkdensitet, hållfasthet och finfraktioner. Resultatindikatorerna R^2 och Q^2 visar att dessa modeller är tillitsfulla. Vidare visar resultatet på liknande mönster mellan kassava och stärkelse som tillsats. Bulkdensiteten påverkades svagt positivt av båda additiven. Hållfastheten påverkades tydligt av kassavan och stärkelsen där stärkelsen kan ses ha något bättre effekt på fuktiga material (14 % fukthalt) men likvärdig effekt som kassavan på torrare material (11 % fukthalt). Högst hållfasthet kunde återfinnas där kassava tillsattes till ett torrt råmaterial (11 % fukthalt). Båda additiven hade en negativ effekt på andelen finfraktion. Resultaten från studien visade att kassavastammar kan användas som ett substitut till raffinerad stärkelse för att öka hållfastheten på biobränslepellets.

Nyckelord: Hållfasthet, bulkdensitet, finfraktion, kvalitet, skördereste

Introduction

Background

In biomass fuel pelletizing, some raw materials with less favorable binding properties may require a binding enhancing additive. Examples of feedstock that give rise to low pellet durability (compared to current standards (EN, 14961-1:2010)) are: eucalyptus (Gil et al., 2010), poultry litter (McMullan et al., 2004), corn stover (Kaliyan & Morey, 2005) and fresh pinewood (Samuelsson et al., 2012).

One way to reach higher durability in pellets is using additives. Such additives are e.g. lignin (Kuokkanen et al., 2011, Nielsen, 2009), starch (Ståhl et al., 2012, Kaliyan & Vance Morey, 2009, Nielsen, 2009, Finney et al., 2009, Pichler et al., 2006, Kuokkanen et al., 2011), proteins (Kaliyan & Vance Morey, 2009) and caustic soda (Finney et al., 2009).

Starch is tightly bond in granules; the granules are built by crystalline and amorphous areas. Those are, as explained by Baumann & Conner (1994), “arranged radially in concentric layers”. To open up those granules it needs to be modified. One of the simplest methods is heating. When heating up starch its gelatinization starts between 57 and 72 °C and due to the friction in the pelletizing die those temperatures are easily achieved. Higher temperatures start a solubilisation and when starch is set to cool down it re-associates into aggregates and forms once again a gel (Jobling, 2004). An average starch contains 20-25 % amylose and 75-80 % amylopectin (Brown & Poon, 2011, Jobling, 2004).

Ståhl et al. (2012) conducted pelletizing experiments with different types of starch additives, natural and oxidized, at various concentrations. They found that starch correlated positively with pellet durability and bulk density and negatively with pelletizer energy consumption. Pichler et al. (2006) used corn starch and could see a lowered abrasion with higher percentage of starch.

However, pure starch addition is a costly additive. In a study performed by Kuokkanen et al. (2011) potato flour and potato peel, starch-containing industrial wastes, was used as additives in wood pellet production. Both additions increased pellet durability and was economically and environmentally favorable.

Another crop with high starch content is cassava (*Manihot esculenta* Crantz). The annual production of cassava roots is 257 billion kg, of which 94 % is produced in equatorial Africa, South-Eastern Asia and South America (FAO, 2012). According to Pelaez et al. (2013) up to 40 % of the total mass is found in the stems and Zhu et al. (2013) estimates the annual world production of dried cassava stems to 35 billion kg. About 10-20 % are used for propagation and the rest is often burned or left at the cropping site, considered as waste (Pelaez et al., 2013, Zhu et al., 2013). Therefore cassava stems should be of interest in the biofuel industry.

According to Zhu et al. (2013) the starch content in cassava stems of the specie SC 205 varies with a mean value of 30.2 % of dry mass. They also endorse further research on how those “left-over crop materials” could be used as fuel as it is an unused source of biomass.

One problem with the cassava stems is that they, this far, is a quite unknown area of research. There are none or little studies today on the chemical structure of the starch in the cassava stems and little studies on the utilization of cassava stems in industrial use. One of the few areas that have been researched the last three years is the possibilities of using cassava stems for bioethanol production (Han et al., 2011, Nuwamanya et al., 2012, Pelaez et al., 2013).

Objective

The goal of this thesis was to evaluate the effects of adding residues from cassava cultivation in comparison to conventional refined starch addition when producing biofuel pellets. Fresh pinewood, known to give rise to low pellet quality, mixed 50/50 with spruce was used as model material to which the starch and cassava residues was used as additives.

The main goal is to find out if cassava residues could be used as an additive in biofuel pellet production, replacing addition of refined starch.

Responses compared were: pellet durability, pellet bulk density, amount of fines in production, energy consumption and production stability.

Materials and methods

Materials

The bulk raw material for production was a sawdust blend of Scots pine (*Pinus sylvestris* L.) and Norwegian spruce (*Picea abies* (L.) H. Karst) by Neova and delivered in big bags. The sawdust, mixed 50/50 spruce/pine, was hammer milled (screen size: 4mm) (Hammer Mill Vertica DFZK-1, Bühler AG, Switzerland) and had a moisture content of ~10 % after milling. The cassava stems originated from Guangxi, China, and was from a variety called South China 205 (SC205) which is one of the leading cultivars in the region. The starch content in the cassava stems were ~26 %. Dried cassava (~8% moisture content) came in bales that were knife milled (Pulverisette 19, Fritsch GmbH, Germany) down to a particle size of < 1 mm. Cassava or starch powder was added to the milled sawdust during mixing in a mixer wagon, carefully trying to achieve a homogeneous blending.

Results from previous pelletizing test runs, suggested a raw material moisture content range of 11-14 % for the pelletizing experimental design. To achieve, for each experimental setting, the right raw material moisture content, water was added slowly through a sprinkling system during mixing in a mixing wagon. Prepared materials were then stored in silos until pelletizing.

Experimental design

Pelletizing was executed in two parallel (one for starch addition and one for cassava residue addition) two-level full factorial designs with three factors, plus three replicate mid-points. Varied factors were, as seen in Table 1: raw material moisture content; ranging from 11to 14 % (wet basis) and a raw material temperature: ranging from 20 to 55 °C (corresponding to a steam addition of 0 and 6 kg/h). Cassava addition ranged from 0 to 5 % and starch addition ranged from 0 to 1 %. Settings with 0 % additive addition were identical for both designs and thus, one could be excluded from the experimental series. The full experimental series contained 18 pelletizing experiments. Runs with cassava was called Cas1-Cas11 and with starch St12-St18.

Table 1. Factor settings for the 18 pelletizing experiments.

Run	Cassava/Starch content (%)	Moisture content (%)	Material temperature (°C)
Cas1	0	11	20
Cas2	5	14	20
Cas3	5	11	20
Cas4	2.5	12.5	38.5
Cas5	0	14	20
Cas6	2.5	12.5	38.5
Cas7	5	11	55
Cas8	0	14	55
Cas9	2.5	12.5	38.5
Cas10	0	11	55
Cas11	5	14	55
St12	1	14	20
St13	1	11	20
St14	0.5	12.5	38.5
St15	0.5	12.5	38.5
St16	1	11	55
St17	1	14	55
St18	0.5	12.5	38.5

Pelletizing experiments

Pelletizing was conducted at the Biofuel Technology Centre (Swedish University of Agricultural Sciences) pilot plant using a SPC 300 Compact pelletizer (Sweden Power Chippers AB, Sweden) with a fixed die. The die channel length was 52.5 mm and the die channel diameter 8 mm. Production rate was adjusted towards 180 kg/h.

For each run, approximately 70 kg material was pelletized. The first run each day had more material, around 100 kg, to allow start up and stabilization of die temperature. Each run had three, two minute long, sampling periods during which pellets were sampled and measurements for pellet temperature was taken. Pellets sampled for further pellet quality analysis and analysis of cold pellets moisture content were put in open plastic containers and set aside to cool down over night. Pellet sampled for hot pellet moisture content analysis were sealed immediately in plastic bags.

For each run, ingoing raw material was collected and sealed in a plastic bag for raw material moisture content analysis.

During the runs: Cas1, Cas10, St16 and St17, data from three measurement periods couldn't be collected, but data were collected from fewer samples. Due to a too dry material or to the combination of high steam and starch addition, these runs hade a very uneven pellet production rate or ended up in a total stop. Material temperature for run St16 and St17 are values, derived from the log, from just before the pellet production stopped.

Measurements and analysis

Pellet temperature, die temperature, and material temperature were measured with a Testo 177-t4 (Testo AG, Germany) at 0.1 Hz frequency. Pellet temperature was measured using a handheld IR-thermometer (Optris, Optris GmbH, Germany) directed towards one die channel outlet when a pellet was coming out of the die. The pelletizer current was measured with a SatelLite U (Mitec Instruments, Sweden) at 1 Hz frequency. All values were measured continuously and logged with EasyView 5.7.0.1 (Intab Interface-teknik AB, Sweden) for later extraction of data corresponding to each measurement period.

Pellets and raw material were analyzed according to CEN standards for moisture content (EN, 14774-1:2009) and pellets were analyzed for bulk density (EN, 15103:2010) and durability (EN, 15210-1:2010). Fine fraction analysis was performed with a sieve with a sieve opening of 3.15 mm. Samples were weighed before and after sieving and the percentages of fine fractions were calculated.

The stability of the pelletizing process was diagnosed by calculating the coefficient of variation, CV_A, of the pelletizer motor current, defined as:

$$CV_A = \frac{\sigma}{\mu} \qquad \text{Equation 1}$$

where σ is the standard deviation and μ is the mean value of the pelletizer motor current during the measurement period. This is a measure on how much the motor current, and indirectly pellet production, varies. This method has previously been used by Larsson et al. (2008) for illustration of process instability in pellet production.

Modelling and diagnostics

The experimental design and modelling of responses was performed in Modde 9.1.0.0 (Umetrics AB, Sweden). Multiple linear regressions (MLR) models were created from varied factors for modelling and prediction of responses. Response models were visualized in surface plots (Eriksson, 2008).

Modde gives two model performance indicators, Q^2 and R^2 defined by Eriksson (2008) as:

$$Q^2 = \frac{SS - PRESS}{SS} \qquad \text{Equation 2}$$

where $PRESS = \sum_i \frac{(Y_i - \hat{Y}_i)^2}{(1-h_i)^2}$ Equation 3

$R^2 = \frac{(SS - SS_{resid})}{SS}$ Equation 4

R^2 is called goodness of fit and indicates how good the model can fit the data. Q^2 is called goodness of prediction and indicates the predictive power of the regression model. To get a good model the aim is a high Q^2. This is done in Modde by empirically excluding regression coefficients with the goal to maximize Q^2. Eriksson (2008) explains that a Q^2 should be considered good if > 0.5 and that the difference between Q^2 and R^2 should be < 0.2 - 0.3.

Further model evaluation was made by calculation of the root mean square error of estimation, RMSEE. RMSEE is calculated by looking at the model predict response values (y_{pred}) and compare those with our observed response values (y_{obs}) according to:

$RMSEE\ or\ RMSECV = \sqrt{\frac{\Sigma(y_{obs} - y_{pred})^2}{n}}$ Equation 5

Further model evaluation were performed by calculating the root mean square error with a cross validation, called RMSECV. RMSECV is calculated by systematically excluding observations and building models with the remaining ones and from the excluded observation calculating (y_{pred})-(y_{obs}). After the first calculation is done the process is repeated while excluding the second experiment and so on. RMSECV is then calculated according to Equation 5 (Wold, 1978).

Results

Mean values (n=3) for achieved factor values, and measured responses for all runs are shown in Table 2. Achieved factor values for moisture content complied good with the settings whereas material temperature was more difficult to control. Pellet bulk density ranged from 449 to 602 kg/m^3, pellet durability ranged from 64.9 to 93.1 % and the amount of fines from 0.7 to 8.0 %. Furthermore the pelletizer motor current averaged around 27 A ranging from 25.2 to 29.0 A. The required current for idle running was 17.0 A. Pellet temperature was pending from 84.3 to 105.6 °C and die temperature between 57.8 to 81.5 °C. Due to feeding problems during run St16 and St17 reliable response values couldn't be obtained, and thus, those runs were excluded from the modelling. Thus, compared to the cassava models that were based on 11 observations (Table 3), response modelling for starch addition was based on 9 observations (Table 4).

No good models could be found for the pelletizer current, CVa and pellet temperature. Therefore those were left out of further data analysis.

Some pellet temperatures are missing; this is due to the construction of the die. Sometimes there weren't any pellets being pressed through the die at the measurement point.

When building the models the die temperature was tested as an uncontrollable factor but no significant models could be attained with those settings.

Cas1, St16 and St17 only have 1 sample and Cas10 and Cas18 only have two samples. These runs had an overall unstable production as well as several production stops, stops that derived mostly from feeding problems.

Table 2. Mean values of achieved factor and measured response values. 95% confidence intervals of mean values in brackets, n=3

	Achieved factor values			Responses						
Run	Cassava / Starch content (%)	Moisture content (%)	Material temperature (°C)	Pellet bulk density (kg/m^3)	Pellet durability (%)	Fines (%)	Pelletizer motor current (A)	Pellet temperature (°C)	CV. pelletizer motor current	Die temperature (°C)
Cas1	0	11.3	23.1	602 (N/A n=1)	84.1 (N/A n=1)	2.1 (N/A n=1)	27.5 (N/A n=1)	96.3 (N/A n=1)	0.147 (N/A n=1)	61.9 (N/A n=1)
Cas2	5	13.5	24.7	496 (0.02)	81.9 (0.03)	1.5 (0.01)	25.4 (0.01)	96.8 (0.01)	0.116 (0.01)	67.8 (0.01)
Cas3	5	11.4	24.7	595 (0.02)	91.7 (0.01)	0.8 (0.00)	29.0 (0.02)	92.5 (0.10)	0.128 (0.02)	67.6 (0.02)
Cas4	2.5	12.7	39.4	533 (0.00)	83.5 (0.01)	1.6 (0.00)	27.7 (0.00)	101.0 (0.00)	0.128 (0.00)	70.2 (0.01)
Cas5	0	14	23.5	499 (0.01)	69.9 (0.02)	3.6 (0.00)	27.5 (0.01)	97.7 (0.01)	0.113 (0.03)	61.8 (0.05)
Cas6	2.5	12.7	31.0	559 (0.02)	87.4 (0.01)	1.2 (0.00)	27.3 (0.00)	98.6 (0.00)	0.100 (0.01)	69.3 (0.01)
Cas7	5	11.3	46.5	560 (0.02)	93.1 (0.02)	0.8 (0.00)	25.2 (0.00)	102.8 (0.00)	0.075 (0.02)	76.2 (0.03)
Cas8	0	13.7	50.5	449 (0.01)	64.9 (0.02)	8.0 (0.01)	25.7 (0.00)	98.8 (0.02)	0.124 (0.00)	77.2 (0.01)
Cas9	2.5	14.3	28.1	536 (0.01)	87.5 (0.03)	1.2 (0.00)	27.3 (0.00)	84.3 (0.19)	0.105 (0.03)	57.8 (0.03)
Cas10	0	11	46.2	557 (0.03)	83.9 (0.07)	1.8 (0.01)	25.6 (0.07)	N/A	0.110 (0.14)	69.8 (0.04)
Cas11	5	13.9	46.9	449 (0.01)	77.7 (0.02)	2.7 (0.00)	26.0 (0.00)	97.9 (0.02)	0.116 (0.01)	74.5 (0.01)
St12	1	13.9	23.3	529 (0.01)	91.3 (0.02)	0.8 (0.00)	27.1 (0.01)	96.6 (0.02)	0.065 (0.00)	58.5 (0.08)
St13	1	12.2	24.6	599 (0.01)	92.1 (0.02)	0.9 (0.00)	28.9 (0.01)	105.6 (0.00)	0.103 (0.02)	73.4 (0.01)
St14	0.5	12.4	28.1	557 (0.00)	89.0 (0.01)	1.0 (0.00)	28.7 (0.00)	96.0 (0.03)	0.105 (0.01)	70.1 (0.01)
St15	0.5	12.5	38.3	507 (0.01)	85.6 (0.03)	1.1 (0.00)	27.6 (0.02)	92.1 (N/A n=1)	0.071 (0.02)	59.1 (0.06)
St16[1]	1	11.2	52.0[2]	492 (N/A n=1)	88.2 (N/A n=1)	0.7 (N/A n=1)	N/A	N/A	N/A	73.0[2] (N/A n=1)
St17[1]	1	13.9	55.0[2]	489 (N/A n=1)	85.4 (N/A n=1)	1.3 (N/A n=1)	N/A	N/A	N/A	N/A
St18	0.5	12.7	29.1	526 (0.01)	87.7 (0.01)	1.8 (0.01)	26.8 (0.02)	103.5 (0.02)	0.075 (0.01)	81.5 (0.02)

[1]Excluded runs. [2] Uncertain values. N/A = missing values

Model statistics for the responses pellet bulk density, pellet durability and fines are shown in Table 3 (Cassava) and Table 4 (Starch). The correlation coefficient, R^2, was excellent (>95), and the prediction coefficient, Q^2, was high (>75) for all models. Due to the factors being range scaled, individual effects of each factor can be compared for each model by the size and sign of the coefficients. By increasing raw material moisture content and steam addition (material temperatures) bulk density and durability decrease, whereas increasing the amount of starch and cassava increase durability and decrease the amount of fines. The models for fines are logarithmic transformed due to the skewness of the dataset.

Table 3. Model performance indicators for Cassava

	Cassava		
Model	Pellet bulk density (kg/m^3)	Pellet durability (%)	log Fines (%)
Number of observations	11	11	11
R^2	0.984	0.984	0.965
Q^2	0.898	0.938	0.806
Degrees of freedom	5	5	5
RMSEE	6.30	1.03	0.334
RMSECV	15.9	2.05	0.762
Coefficients			
Constant	549	86.2	0.132
Moisture content (m)	-60.4 (0.00)	-8.74 (0.00)	0.257 (0.00)
Cassava content (c)	1.97 (0.58)	5.97 (0.00)	-0.227 (0.00)
Material temperature	-37.9 (0.00)	-2.72 (0.02)	0.137 (0.02)
m * m	25.2 (0.02)	7.05 (0.00)	-0.221 (0.02)
c * c	-45.0 (0.00)	-10.6 (0.00)	0.340 (0.00)

In brackets are p-values at a 95 % confidence interval.

Table 4. Model performance indicators for Starch

	Starch		
Model	Pellet bulk density (kg/m^3)	Pellet durability (%)	log Fines (%)
Number of observations	9	9	9
R^2	0.983	0.993	0.952
Q^2	0.938	0.919	0.751
Degrees of freedom	4	3	3
RMSEE	5.950	0.740	0.303
RMSECV	11.431	2.541	1.343
Coefficients			
Constant	517	86.5	0.126
Moisture content (m)	-57.4 (0.00)	-4.98 (0.01)	0.250 (0.03)
Starch content (s)	14.6 (0.02)	7.03 (0.00)	-0.385 (0.01)
Material temperature	-43.0 (0.00)	-3.35 (0.03)	0.105 (0.26)
m * m	---	---	-0.450 (0.09)
s * s	19.9 (0.04)	-4.07 (0.02)	0.373 (0.07)
m * s	---	4.02 (0.02)	---

In brackets are p-values at a 95 % confidence interval. --- = excluded coefficients

Prediction surface plots are rendered for bulk density, durability and fines. Figure 1-3 shows prediction plots for cassava and Figure 4-6 for starch for each response; pellet bulk density, pellet durability and amount of fines.

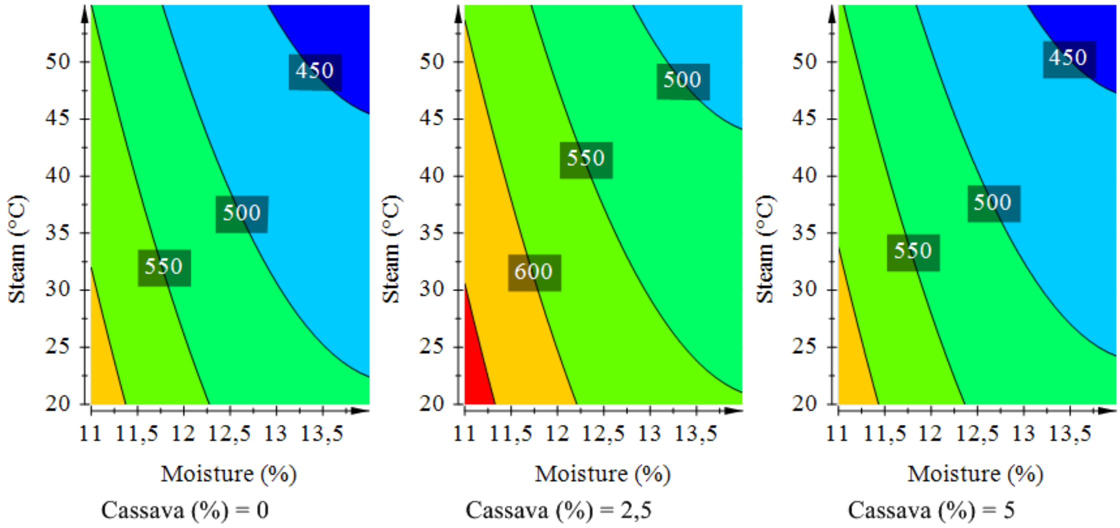

Figure 1. Prediction plot for pellet bulk density (kg/m^3) when cassava is used.

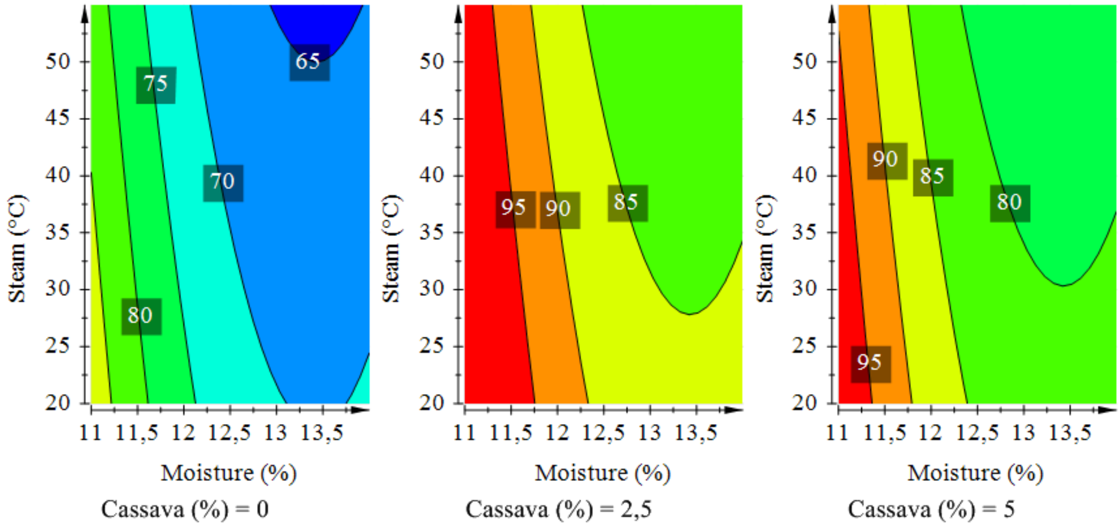

Figure 2. Prediction plot for pellet durability (%) when cassava is used.

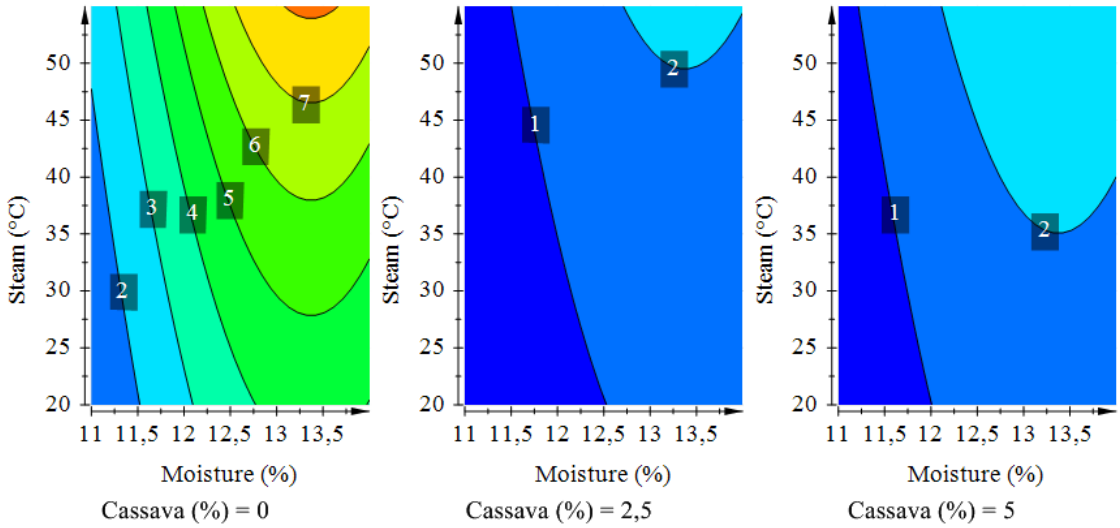

Figure 3. Prediction plot for fines (%) when cassava is used.

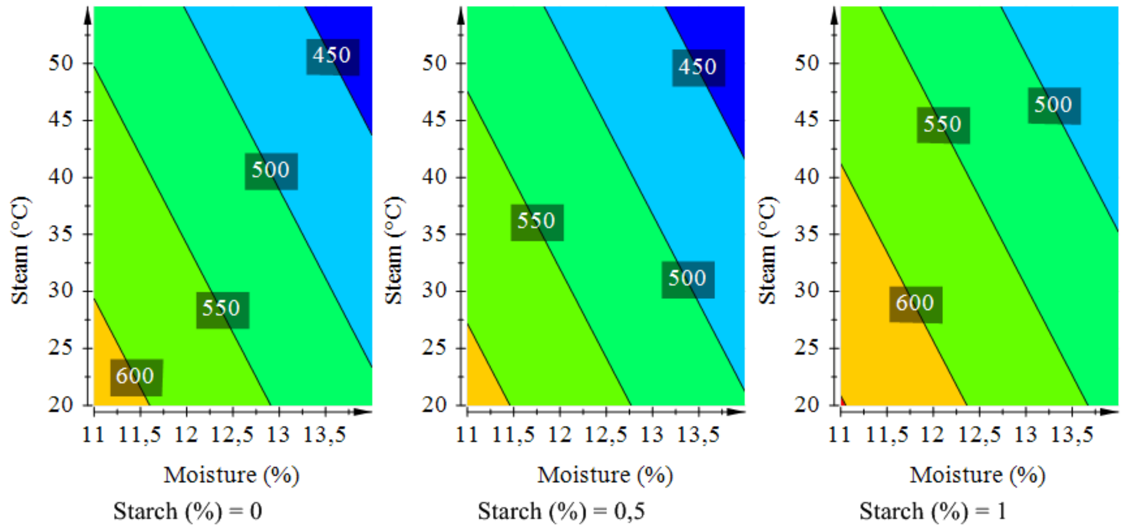

Figure 4. Prediction plot for bulk density (kg/m^3) when starch is used.

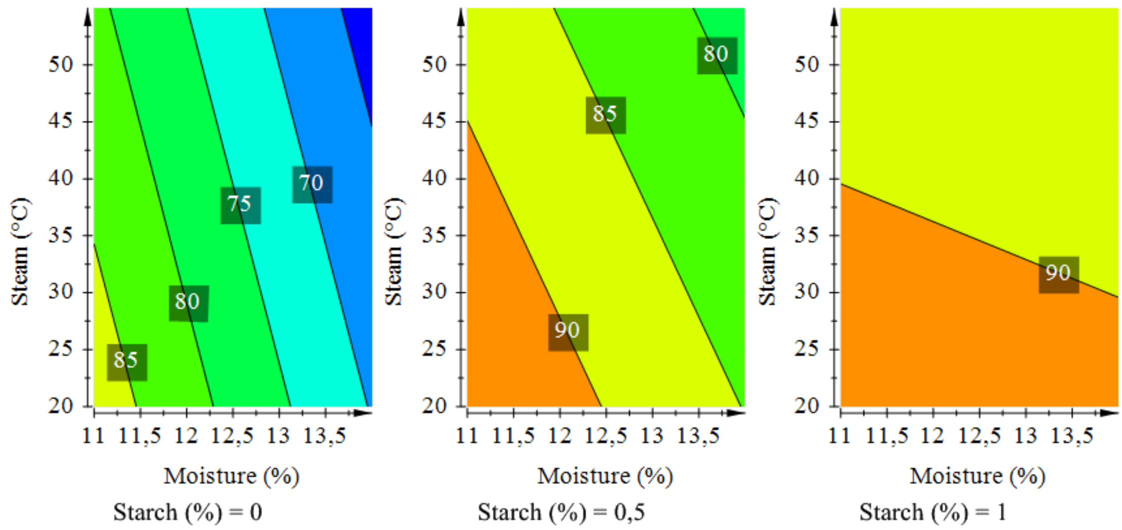

Figure 5. Prediction plot for durability (%) when starch is used.

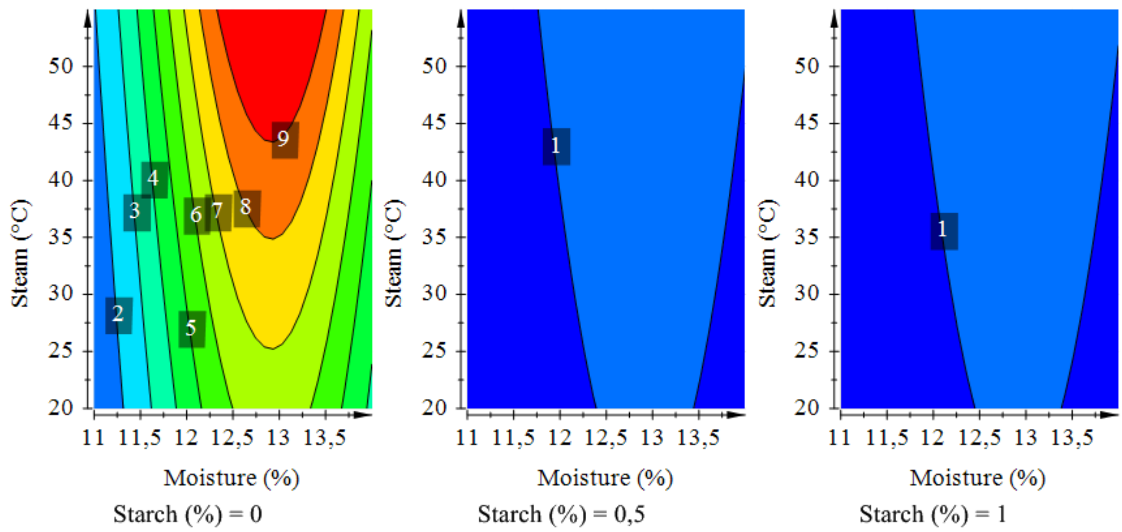

Figure 6. Prediction plot for fines (%) when starch is used.

Discussion

Model parameters

The model performance indicators R^2 and Q^2 were overall high. As Eriksson (2008) explained, a Q^2 should be considered good if > 0.5 and that the difference between Q^2 and R^2 should be < 0.2-0.3, and those two criteria are fulfilled.

When looking at the RMSECV and the RMSEE the errors for the bulk density and the durability are, ±1-3%. However for the fines the RMSECV goes up to: for cassava ±33% and for starch ±64% (RMSECV of 1.34 and an average value for fines at 3.08). Due to the very high amount of fines in Cas 8 the nature of the response distribution becomes skewed, in this case a positive skewness. To get a better model estimation a logarithmic transformation was conducted for the models for fines.

Coefficients

Moisture content is the most influential coefficient for bulk density for both the starch and the cassava models. For modeling pellet durability, the square of cassava content and the starch content, respectively, had the largest coefficients. Models for the amount of fines had the largest coefficients for cassava and starch content, respectively.

There is a lot of resemblance between the models with cassava and the models with starch and their coefficients generally had the same leverage on the model.

Could cassava be used instead of pure starch?

Both cassava and starch increase pellet durability. Comparing the otherwise equal runs Cas2 and St12 shows a difference of 10% in pellet durability in favor for St12 but at lower moisture contents, as for Cas3 and St13, the difference is only 0.4 %, again starch is the better. This is also verified when comparing Figure 2 vs Figure 5, where cassava has higher peaks with a steeper curve and starch has a flatter curve. According to this study cassava could lack some effect on moist materials and the effect of cassava addition has an optimum closer to 2.5 % than 5 %. Looking at pellet bulk density and amount of fines the prediction plots are almost identical, where both cassava and starch have a good effect, increasing pellet bulk density and decreasing amount of fines.

The resemblance between the two additions could be seen when comparing two runs with equal settings e.g.:
Cas3 with; pellet bulk density at 595 kg/m^3, pellet durability at 91.7 % and an amount of fines at 0.8 %.
St13 with; pellet bulk density at 599 kg/m^3, pellet durability at 92.1 % and an amount of fines at 0.9 %

Comparison with other studies

What follows will be a comparison with Samuelsson et al. 2009 and Samuelsson et al. 2012 where similar factor settings and fresh pine wood were used.

This study has overall low bulk densities (449 – 602 kg/m^3). For example Samuelsson et al. (2009) have bulk densities between 507 and 679 kg/m^3 and Samuelsson et al. (2012) have densities between 523 and 712 kg/m^3. This difference could be explained by lower moisture content in the studies by Samuelsson et al.

Samuelsson et al. (2009) have durabilities between 78.9 and 97.8 % which is higher than in this study but Samuelsson et al. (2012) have durabilities between 61.8 and 89.4 % which is more equal to this study's 64.9 – 84.1 %.

Samuelsson et al. (2009) have amounts of fines that varies between 1.0 and 5.5 % and Samuelsson et al. (2012) between 2.9 and 8.4 %, both similar to this study's 1.8 to 8.0 %.

These three parameters seem to be comparable with Samuelsson et al.'s results. And interesting to notice is that when cassava and starch is introduced the durability can be improved with up to 20.5 % (from 64.9 to 85.4 %). This effect seems to be higher for moist materials but dry materials tends to give rise to higher durabilities.

The prediction plots correspond well with the results of Samuelsson et al. (2012). Their durability optimum for fresh material was between 9-10% MC. In this study the durability tends to increase with lowered moisture content with an unknown maximum under 11% MC.

One thing to consider is the starch content in the stems. My material had ~26 % but according to Zhu et al. (2013) this amount could range from 22 – 39 %. How the pellet reacts when using stems with higher starch content could be an interesting and possible future study. This should also be considered if trying to implement these results on larger scale.

Zhu et al (2013) also have a good point in the environmental debate where they can see a great potential in a harmonized production where both fuel and food is produced in the same land areas without competing purposes.

What could have been changed?

The small difference in pellet durability and pellet bulk density between this study and the ones by Samuelsson could be derived from the die channel length. The die channel length was now 52.5 mm while Samuelsson et al 2009 & 2012 used 55 mm. The moist materials ran through the die with a low resistance. This resulted in pellets, as Cas8, with a low bulk density, a low durability and a high percentage of fines. With a thicker die a higher bulk density, and possibly a higher durability, could have been reached, as shown by Högqvist et al. (2012).

It would be interesting to try other wood materials where low durability is noticed as in the case with eucalyptus, which seems to have problem with high abrasion levels (Gil et al. (2010)) but also the other materials mentioned in the introduction.

Deeper analysis of the cassava material should have been done early in the process to get a more correct matching between proportions of the stems cassava and the refined starch (which consist of almost pure starch). Early assumptions were a 5 to1 proportion between their starch contents. While knowing that there is 26 % starch in the stems it is closer to a 4 to 1 proportion. This could explain the small difference, in the cassavas favor, between the prediction plots for cassava and starch.

Conclusions

In this study, where a mixture of spruce and pine was pelletized, using cassava stems as additive had similar effect as starch addition, by increasing the durability of produced pellets.

Starch and cassava had the same effect on durability at low moisture contents whereas starch had better effect at higher moisture contents.

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