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MODELAGEM DE EQUAÇÕES ALOMÉTRICAS PARA ESTIMATIVA DO PODER CALORÍFICO ÚTIL DE *Eucalyptus* sp. [1]

Caroline Junqueira Sartori [2]
Thaissa Gomes Corrêa
Dalila de Oliveira Santos
Bruno Oliveira Lafetá
Adrielly Rodrigues Nascimento

RESUMO

Este trabalho objetivou obter equações para estimar o Poder Calorífico Útil (PCU) de compartimentos arbóreos de *Eucalyptus* sp. por meio de variáveis alométricas. Foram abatidas 32 árvores, das quais foram coletadas subamostras de folhas, galhos, cascas e madeira; e determinados os poderes caloríficos superior, inferior e útil de cada componente – nesse caso, as equações foram definidas pela relação entre o PCU e as variáveis alométricas, como Diâmetro à Altura do Peito (DAP), Altura Total (AT) e espaçamento. As duas melhores equações para estimar o PCU corresponderam à madeira, relevantes a 1% para ao menos uma variável não destrutiva, por representarem menores Raízes Quadráticas de Erros Médios (RQEMs) e Critérios de Informação de Akaike (CIA), bem como melhores valores de correlação de Pearson (r). Vale ressaltar que apenas as dimensões do DAP e da AT influenciaram o PCU da madeira.

Palavras-chave: Variáveis alométricas. Energia de biomassa florestal. Resíduos florestais.

MODELING ALLOMETRIC EQUATIONS TO ESTIMATE USEFUL CALORIFIC VALUE OF *Eucalyptus* sp.

ABSTRACT

This work aimed to obtain equations to estimate the Useful Calorific Value (UCV) of tree compartments of *Eucalyptus* sp. through allometric variables. Thirty-two trees were felled, from which sub-samples of leaves, branches, bark, and wood were collected; and the higher, inferior and useful calorific values of each component were determined – in this case, the equations were determined through the relation between UCV and allometric variables, such as Diameter at Breast Height (DBH), Total Height (TH) and spacing. The two best equations for estimating UCV corresponded to wood, relevant at 1% for at least one non-destructive variable. They presented lower Root Mean Squared Error (RMSE) and Akaike Information Criteria (AIC), as well as better Pearson correlation values (r). It is worth mentioning that only the dimensions of DBH and TH influenced on the UCV of wood.

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[2] **Autor correspondente:** Caroline Junqueira Sartori, e-mail: caroline.sartori@ifmg.edu.br

Keywords: Allometric variables. Forest biomass energy. Forest residues.

1 INTRODUCTION

In a comparison to the rest of the world, Brazil has stood out for having a clean energy matrix, basically due to the high share of renewable sources in the domestic energy supply, which represents 83% of the total in 2019 when added to imports (BRAND *et al.*, 2014; TOLMASQUIM; GUERREIRO; GORINI, 2007; EPE, 2019). Then, wood is highlighted for its abundance and for being the oldest fuel used for energy purposes (BERSCH *et al.*, 2018).

Cogitating about the national energy scenario, firewood occupies an important position, being a renewable natural resource that may have a sustainable production but present the polluting characteristics of other fossil sources (ELOY *et al.*, 2014). With an area of nine million hectares of reforestation in 2019, Brazilian planted tree sector is one of the greatest potential segments to contribute for building a green economy – in this situation, 6.97 million hectares (77%) corresponded to plantations of Eucalyptus genus (IBÁ, 2020), and a large part of this production is destined for energy purposes.

Wood corresponds to the main biomass in the arboreal compartment, as verified by Guimarães *et al.* (2015) in a four-year-old *Eucalyptus dunnii* stand. According to the same author, 63% of the biomass is located in wood, and the rest is considered harvest residues, followed by roots (14%), branches (11%), bark (8%) and leaves (4%). Meanwhile, Castro *et al.* (2017) argument the loss of bark biomass in the harvesting process is compatible to 25.7%.

In this circumstance, forestry sector residues are generated from harvesting to the final product, which are important sources of biomass (PINCELLI *et al.*, 2017). Considering the chemical composition and the abundance of residual biomass, they can be sustainably implemented as a source of renewable energy. So, the volume of waste in Eucalyptus logs in sawmills is 56.2%, as verified by Monteiro *et al.* (2017).

Researches aimed at applying the applicability of equations to estimate the energy production of trees, and mainly non-destructive variables are important because they contribute to cost reduction and faster results. Thus, the objective of this work was to model equations using the allometric variables of Total Height (TH), spacing and Diameter at Breast Height (DBH), estimating Useful Calorific Value (UCV) of *Eucalyptus* sp.

2 MATERIAL AND METHODS

The study was accomplished in a *Eucalyptus* stand located in São João Evangelista, Minas Gerais, Brazil. Located in the Rio Doce hydrographic basin (Suaçuí Grande sub-basin), in the Center-Northeast region of the referred state, the municipality has the geographic coordinates 18°32' 52" of south latitude and 42°45'48" of longitude West and average altitude of 690 meters. The climate is classified as mild temperate, dry winter and hot/rainy summer (CWA), with an average temperature of 15 °C and annual rainfall of 1,081 mm (IBGE, 2014).

The experiment was installed in May 2012 using a hybrid of *Eucalyptus grandis* Hill ex Maiden *versus Eucalyptus urophylla* S. T. Blake. The experimental design was in three randomized blocks, with the treatments being constituted in the following technique: T1: 3.0 x 0.5 m spacing – 6.667 plants/ha^{-1}; T2: 3.0 x 1.0 m – 3.333 plants/ha^{-1}; T3: 3.0 x 1.5 m – 2.222 plants ha^{-1}; and T4: 3.0 x 2.0 m – 1.667 plants ha^{-1}. Each experimental unit was defined by four planting lines with seven plants, totaling 28 individuals, of which 10 were measured, adopting a simple border.

At 56 months of age, the forest inventory was achieved by measuring the DBH at height of 1.30 m from the ground with bark and the TH (H, m) with an electronic Haglof hypsometer of all the shafts. After the forest inventory, four diametric classes were established with regular intervals per treatment, based on the Diameter Variation Amplitude (DAP) – class sizes varied between planting spacing. Two trees were felled per diameter class and treatment, totaling 32 individuals.

Subsamples of arboreal components of leaves, branches, bark, and wood were collected, stored in closed plastic packaging and immediately taken to the laboratory, for moisture determination by the gravimetric method. For the wood sampling, discs of about six centimeters thick were removed at the positions of 0%, 25%, 50%, 75% and 100% of the commercial height, as well as the trunk DBH for the moisture determination. Samples of all tree components were ground in a Wiley type mill, sieved with a set of 40 and 60 mesh sieves and dried to determine the Higher Calorific Value (HCV). For instance, the HCV was determined by approximately 0.3 g of ground and dry sample of each tree component. The samples were analyzed in a digital calorimeter IKA C 200, and the test was standardized with ABNT NBR 8633 standard (ABNT, 1984).

In turn, the calculation of the Lower Calorific Value (LCV) was made using the percentage of hydrogen present in the material of each tree component, in accordance to literature. For wood and twig, the value of 6% of hydrogen was adopted (SILVA, 2001); for bark, 5.66% (RODRIGUES, 2018); and for leaves, 7.12% (PÉREZ *et al.*, 2006).

The LCV was determined according to the Equation 1:

$$LCV = HCV - 600 * \left(\frac{9*H}{100}\right) \qquad \text{Eq. 1}$$

Being:

LCV = Lower Calorific Value (kcal/kg)

HCV = Higher Calorific Value (kcal/kg)

H = hydrogen content (%).

The UCV was determined according to Equation 2, in order to estimate the energy that could be released from burning forests under the conditions at the study period as a function of their moisture:

$$UCV = LCV \left(\frac{100-U}{100}\right) - 6 * U \qquad \text{Eq. 2}$$

Being:

UCV = Useful Calorific Value (kcal/kg)

U = moisture on wet basis (%)

The results obtained through the aforementioned equation were used to model the equations, with the aim of estimating the UCV in a representative perspective. To obtain the equations, DBH, the TH of the tree and planting spacing were applied as independent variables. Equations were generated combining the last ones, as shown in Table 1.

Table 1 - Tested equations to estimate Useful Calorific Values of tree components of *Eucalyptus* sp.

Id.	**Equations**
1	$Y = \beta0 + \beta1DBH + \beta2Ht + \beta3Sp + \mathcal{E}$
2	$Y = \beta0 + \beta1DBH + \beta2Ht + \mathcal{E}$
3	$Y = \beta0 + \beta1DBH + \beta2Sp + \mathcal{E}$
4	$Y = \beta0 + \beta1Sp + \beta2Ht + \mathcal{E}$
5	$Y = \beta0 + \beta1Sp + \mathcal{E}$
6	$Y = \beta0 + \beta1DBH + \mathcal{E}$
7	$Y = \beta0 + \beta1Ht + \mathcal{E}$

Id. = Equation identification; Y = useful calorific value (kcal/kg); *Ht* = total height (m); *DBH* = diameter at breast height (cm); Sp= Spacing; $\beta0$, $\beta1$, $\beta2$ e $\beta3$ = regression coefficients.

The homogeneity and normality of the variables were analyzed using the Breush-Pagan and Shapiro-Wilk tests, respectively. The quality of the equation adjustments was evaluated according to the significance of the parameters using the t test, the values of Root Mean Squared Error (RMSE), Akaike Information Criteria (AIC) and Pearson's correlation coefficient (r). Lower RMSE and AIC indexes imply higher predictive quality, and only the equations that met the assumptions aforesaid and low values of deviation were selected for the subsequent analyses.

To diagnose the significant effect, a significance level of 1.0% probability was adopted in all statistical analyses. Data processing and statistical analysis were performed using R 3.6.1 software (R CORE TEAM, 2019).

3 RESULTS AND DISCUSSION

Table 2 comprehends the average values of HCV, LCV, UCV, and Humidity (H) in each compartment, as well as calorific values presented in kcal/kg and MJ/kg:

Table 2 - Higher Calorific Value, Lower Calorific Value, Useful Calorific Value and Humidity in components of *Eucalyptus* sp.

	HCV		**LCV**		**UCV**		**H**
	Kcal/kg	**MJ/kg**	**Kcal/kg**	**MJ/kg**	**Kcal/kg**	**MJ/kg**	**%**
Wood	4402.50	18.40	4078.50	17.10	1664.07	7.00	59.12
Leaves	4906.57	20.50	4582.57	19.20	1641.63	6.90	64.11
Branches	4434.50	18.60	4110.50	17.20	1638.32	6.90	58.97
Barks	3798.80	15.90	3493.16	14.6	1058.31	4.40	69.58

Source: Authors (2023).

For the wood component, mean values of HCV, with 4402.50 kcal/kg (18.4 MJ/kg), LCV, with 4078.50 kcal/kg (17.1 MJ/kg) and UCV, with 1664.07 kcal/kg (7.0 MJ/kg) were found for wood, which had 59.12% of average moisture in the wet base.

Regarding the HCV, values of 4730 kcal/kg (19.8 MJ/kg) in *Eucalyptus grandis* wood were verified by Monteiro *et al.* (2017); 4206.501 kcal/kg (17.6 MJ/kg), in eucalyptus sawdust from sawmills (CHEN *et al.*, 2015), 4565.01 kcal/kg (19.1 MJ/kg), in woods of *E. urophylla*, *E. saligna* and *E. dunnii* (EICHlER, *et al.*, 2017); and 4701.24 kcal/kg (19.67 MJ/kg), in wood from clones of *Eucalyptus grandis versus Eucalyptus urophylla* at different ages, from falls caused by the wind (ZANÚNCIO *et al.*, 2019).

Silva (2012) diagnosed LCV of 4637.56 kcal/kg (19.4 MJ/kg) and 4625.34 kcal/kg (19.4 MJ/kg) for wood from *Eucalyptus urophylla* and *Eucalyptus citriodora*, respectively, which are similar to the results of this study. Concerning UCV, the author found mean values of 2604.95 kcal/kg (12.5 MJ/kg), 2547.89 kcal/kg (10.90 MJ/kg) and 2596.86 kcal/kg (10.86 MJ/kg) for *E. urophylla*, *E. grandis* and *E. citriodora*, a higher value than the one verified in this article, since the wood had an average moisture content of 35%, but for an average moisture content of 55%, the indexes of LCV were 1618.81 kcal/kg, 1579.31 kcal/kg and 1613.21 kcal/kg, correspondingly, which shows the influence of moisture on the energy potential of biomass.

For leaves, there was an average HCV of 4906.57 kcal/kg (20.5 MJ/kg), LCV of 4582.57 kcal/kg (19.2 MJ/kg) and UCV of 1641.63 (6.9 MJ/kg) at an average moisture in the wet base of 64.11%. Regarding the HCV, values of 3561.18 kcal/kg (14.9 MJ/kg) in Eucalyptus leafs residues were verified in the literature (CHEN *et al.*, 2015). Brand *et al.* (2014) understand that *Pinus taeda* leaves mean values of HCV and UCV of 5138.62 kcal/kg (21.5 MJ/kg) and 1625.24 kcal/kg (6.8 MJ/kg), respectively, at a moisture of 58%.

In regard to eucalyptus branches, mean values of 4434.50 kcal/kg (18.6 MJ/kg), 4110.50 kcal/kg (17.2 MJ/kg) and 1638.32 kcal/kg (6.9 MJ/kg) of HCV, LCV and UCV were obtained respectively at average moisture in the wet base of 58.97%. In a study on biomass production for energy generation in *Pinus taeda* stands at different ages, Brand *et al.* (2014) considered mean values of HCV in branches of 4899.62 Kcal/Kg (20.5 MJ/kg) and UCV of 1816.44 Kcal/Kg (7.6 MJ/kg) at a moisture of 54%.

For eucalyptus bark, mean values of 3798.80 kcal/kg (15.9 MJ/kg), 3493.16 kcal/kg (14.6 MJ/kg) and 1058.31 kcal/kg (4.4 MJ/kg) of HCV, LCV and UCV were achieved respectively at average moisture in the wet base of 69.58%. In a comparative research of calorific value of biomass from residual Eucalyptus bark, which was discarded in forests, Cantizani *et al.* (2016) acquired mean values of 4561.96 kcal/kg (19.1 MJ/kg) for HCV, 4227.57 kcal/kg (17.7 MJ/kg) for LCV and 2436.23 kcal/kg (10.2 MJ/kg) for UCV at average moisture of 37%. About HCV, indexes of 3845 kcal/kg (16.1 MJ/kg) in *Eucalyptus grandis* bark were verified in the literature (MONTEIRO *et al.*, 2017); 3585.09 kcal/kg (15.0 MJ/kg) in residual Eucalyptus bark (CHEN *et al.*, 2015); and 3800.19 kcal/kg (15.9 MJ/kg) (CHEN; YU; WEI, 2015) and 4421.61 kcal/kg (18.5 MJ/kg) in residual Eucalyptus bark in China (GAO, *et al.*, 2016).

Garcia *et al.* (2012) investigated different types of materials in Spain – for example, industrial and forest residues, materials from energy crops and cereals. In this conjuncture, the authors noted that most of the studied samples have HCV above 3585.1 kcal/kg (15.0 MJ/kg). Meanwhile, Protásio *et al.* (2013) analyzed energy potential of different types of biomass, such as residues from the processing of *Eucalyptus urophylla* wood, *Toona ciliata* (pink cedar), and *Pinus* sp., rice husk, sugarcane bagasse, coffee residues, corn crop residues, and residual bamboo kraft pulp (*Bambusa vulgaris*). Higher values of HCV and LCV were observed in the residues of *Pinus* sp (4865.29 kcal/kg and 4487.91 kcal/kg, respectively), and this fact corroborates the high values of lignin and extractive content in the material. As for hardwoods, represented by shavings of pink cedar and eucalyptus, they indicated similar values, HCV of 4755.42 and 4571.51 kcal/kg and LCV of 4380.43and 4196.52 kcal/kg, appropriately.

Eloy *et al.* (2014) affirmed that HCV of *Eucalyptus grandis* wood at different ages ranged from 4241 to 4653 kcal/kg, in which the highest indexes were verified for older plants, as the lignin contents increase over the years – this fact corroborates the diameter influence on the calorific value. The study also certified, in comparison with the literature, the strong influence of moisture on the energy potential of biomass.

All equations for estimating the UCV of the leaf, branch and bark met the assumptions of homogeneity and normality at 1% level of significance. To estimate UCV of wood, Equation 2 did not meet the assumptions mentioned above.

The parameters of the equations and the quality statistics (RMSE, AIC and r) used to evaluate the equations are illustrated in Table 3:

Table 3 - Coefficients and statistical parameters of the equations applied to estimate Useful Calorific Value of the tree components of *Eucalyptus* sp.

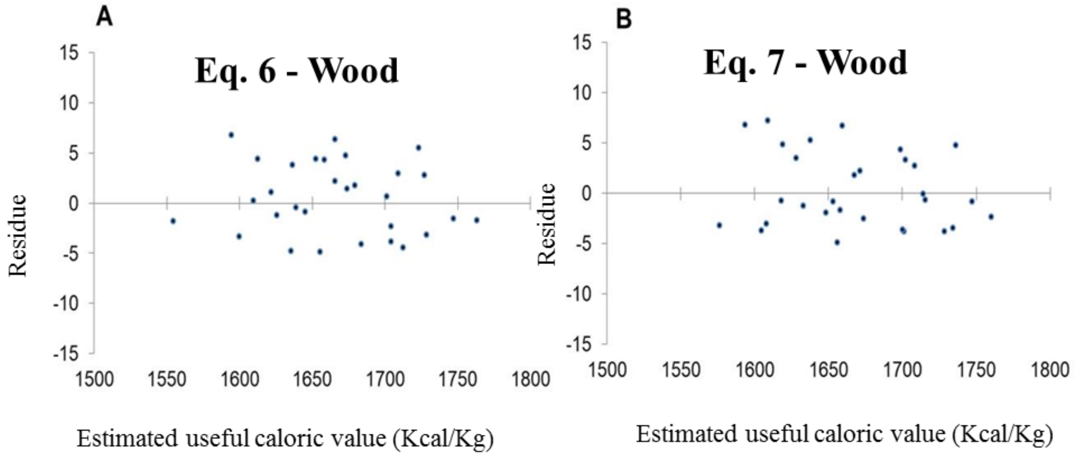
Response Variable (Y)	**Equations**	**β0**	**β1**	**β2**	**β3**	**RMSE**	***r***	**AIC**
				Wood				
Power Calorific Useful Kcal/kg	1	1405.873^{**}	4.038^{ns}	7.839^{ns}	0.323^{ns}	67.745	0.612^{**}	371
	2	1406.082^{**}	4.051^{ns}	7.838^{ns}	-	67.745	0.612^{**}	369
	3	1463.000^{**}	12.240^{**}	0.0638^{ns}	-	69.664	0.581^{**}	370
	4	1395.092^{**}	2.068^{ns}	10.912^{**}	-	68.119	0.606^{**}	369
	5	1633.500^{**}	24.460^{ns}	-	-	84.521	0.159^{ns}	381
	6	1462.743^{**}	12.238^{**}	-	-	69.666	0.581^{**}	368
	7	1369.229^{**}	10.972^{**}	-	-	68.129	0.606^{**}	367
				Leaves				
Power Calorific Useful Kcal/kg	1	1496.853^{**}	$11,373^{ns}$	-3.843^{ns}	$41,184^{ns}$	158.273	0.264^{ns}	425
	2	1523.481^{**}	13.020^{ns}	-3.935^{ns}	-	159.814	0.227^{ns}	424
	3	1468.993^{**}	7.355^{ns}	41.311^{ns}	-	158.473	0.259^{ns}	423
	4	1466.493^{**}	46.098^{ns}	4.814^{ns}	-	159.544	0.233^{ns}	423
	5	1571.970^{**}	55.970^{ns}	-	-	161.063	0.197^{ns}	422

	6	1495.037**	8.911^{ns}	-	-	160.022	0.221^{ns}	422
	7	1491.815**	6.137^{ns}	-	-	161.491	0.177^{ns}	422
Branches								
Power Calorific Useful Kcal/kg	1	1379,748**	-1,881^{ns}	9,257^{ns}	86,820^{ns}	195,491	0,316^{ns}	438
	2	1435,884**	1,591^{ns}	9.063^{ns}	-	200,986	0,236^{ns}	438
	3	1446,861**	7,799^{ns}	86,514^{ns}	-	196,429	0,312^{ns}	437
	4	1384,768**	86,008^{ns}	7,826^{ns}	-	195,519	0,326^{ns}	436
	5	1555,740**	102,060^{ns}	-	-	198,784	0,276^{ns}	436
	6	1501,403**	11,057^{ns}	-	-	201,860	0,217^{ns}	436
	7	1432,013**	10,294^{ns}	-	-	201,006	0,235^{ns}	436
Barks								
Power Calorific Useful Kcal/kg	1	1026.644**	6.086^{ns}	-4.423^{ns}	31.625^{ns}	56.316	0.367^{ns}	359
	2	1047.091**	7.350^{ns}	-4.494^{ns}	-	58.826	0.236^{ns}	360
	3	994.575**	1.460^{ns}	31.771^{ns}	-	57.056	0.334^{ns}	358
	4	1010.398**	34.255^{ns}	0.2087^{ns}	-	57.333	0.321^{ns}	358
	5	1014.960**	34.680^{ns}	-	-	57.341	0.320^{ns}	356
	6	1014.605**	2.657^{ns}	-	-	59.558	0.179^{ns}	358
	7	1029.215**	1.192^{ns}	-	-	60.267	0.093^{ns}	359

$\beta0$, $\beta1$, $\beta2$ e $\beta3$ = regression coefficients; RMSE = Root Mean Squared Error , AIC= Akaike Information Criteria, r = Pearson's correlation coefficient; ** = significant at 1%; and ns = not significant.
Source: Authors (2023).

Referring to UCV of wood, only Equations 6 and 7 exhibited all significant regression coefficients (Table 3) – these calculations were simple input, based on the use of DBH or TH of the shafts as predictor variables. No significant functional relation was established for estimating UCV of the leaf, twig and bark components, and the calorific value averages are shown in Table 2. This lack of regression was evidenced by the presence of non-significant parameters ($p > 0.05$) after adjusting the mathematical models (Table 1).

Hence, residual distribution analyzes of the fitted equations can be verified in Figures 1A and 1B, of Equations 6 and 7, respectively:



Figures 1A and 1B - Graphic analysis of dispersion of the residues of Equations 6 and 7 tested to estimate the Useful Calorific Value of wood.
Source: Authors (2023).

Through the graphical analysis, it is also observed that model follows the assumptions of linearity (no form of linearity deviation), mean residuals around zero and homoscedasticity (keeping constancy on the error variance). In this sense, correlation coefficients were moderate and significant ($0.5 \geq r \leq 0.7$ and $p \leq 0.01$).

According to this study, only the variables DBH and TH demonstrate influence on the UCV of wood. Rosário (2016) states in her study on energy production models that biometric variables, DBH and TH presented the highest correlation with energy production. Related to UCV of wood, Equations 6 and 7, exhibited similar quality of fit statistics, with close values in terms of RQEM, r and AIC. This result has a practical importance, since Equation 6 requires information only on DBH, a variable whose measurement is less laborious and expensive in forest inventories, compared to measuring TH (LAFETÁ *et al.*, 2023). The simplicity in obtaining DAP makes Equation 6 more appropriate and operationally advantageous for estimating UCV of wood.

Studies reporting the influence of variables such as DBH and TH on the UCV of wood were not identified in the literature. Therefore, the importance of this study is highlighted, as it enabled the generation of equations to estimate UCV, which is an excellent parameter to assess the energy potential of biomass fuels through non-destructive methods increasingly used by various forestry and industrial sectors.

4 CONCLUSIONS

The results indicated the potential for estimating UCV through allometric variables, such as DBH and TH; consequently, Equations 6 and 7 were chosen as the best ones to estimate UCV of wood. In different forecast conditions, the knowledge of moisture and hydrogen content, for example, is essential for building a model.

Lastly, equations for estimating UCV of tree components leaf, twig and bark were not combined, since they did not meet the parameters RMSE, AIC and adapted r.

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DADOS DOS AUTORES:

Caroline Junqueira Sartori
E-mail: caroline.sartori@ifmg.edu.br
Curriculum Lattes: http://lattes.cnpq.br/2592345824356941

Engenheira Florestal, pela Universidade Federal de Lavras. Doutora em Ciência e Tecnologia da Madeira pela Universidade Federal de Lavras. Tem experiência na área de Recursos Florestais e Engenharia Florestal, atuando nos seguintes temas: tecnologia da madeira, produtos florestais não madeireiros, taninos e cascas. Atualmente, professora no Instituto Federal de Minas Gerais - IFMG, campus São João Evangelista.

Thaissa Gomes Corrêa
E-mail: thaissasouzac@outlook.com
Curriculum Lattes: http://lattes.cnpq.br/8897257633875565

Bacharel em Engenharia Florestal (2019), com obtenção de título pelo Instituto Federal de Educação, Ciência e Tecnologia de Minas Gerais campus São João Evangelista. Técnico Agrícola com Habilitação em Agropecuária desde 2009 pela mesma instituição. Realizou

estágio obrigatório junto ao Laboratório de Estudos e Projetos em Manejo Florestal (LEMAF) da Universidade Federal de Lavras - MG.

Dalila de Oliveira Santos
E-mail: daliladeoliveirasantos@gmail.com
Curriculum Lattes: http://lattes.cnpq.br/7669483499140208
Graduada em Engenharia Florestal pelo Instituto Federal Minas Gerais (2019).Bolsista pelo CNPq (2017-2019) com trabalho na área de solos, dinâmica de microbacias e serviços ecossistêmicos. Mestre em CIÊNCIA FLORESTAL pela Universidade Federal dos Vales do Jequitinhonha e Mucuri - Campus JK (2023). Doutoranda em CIÊNCIA fLORESTAL pela Universidade Federal dos Vales do Jequitinhonha e Mucuri - Campus JK (ainda em curso).

Bruno Oliveira Lafetá
E-mail: bruno.lafeta@ifmg.edu.br
Curriculum Lattes: http://lattes.cnpq.br/7137536896294497
Doutorado, mestrado e graduação em Engenharia Florestal pela Universidade Federal dos Vales do Jequitinhonha e Mucuri (UFVJM). Atualmente é professor no Instituto Federal de Educação, Ciência e Tecnologia de Minas Gerais (IFMG) -CampusSão João Evangelista. Tem experiência na área de Recursos Florestais e Engenharia Florestal, com ênfase em Silvicultura, Mensuração, Amostragem, Modelagem e Manejo Florestal. Também, atua com redes neurais artificiais, support vector machine (SVM) e Random Forest.

Adrielly Rodrigues Nascimento
E-mail: adrielerodrigues2009@hotmail.com
Curriculum Lattes: http://lattes.cnpq.br/8819765461488526
Graduada em Engenharia Florestal pelo Instituto Federal Minas Gerais. Tem experiência na área de Recursos Florestais e Engenharia Florestal, atuando nos seguintes temas: tecnologia da madeira, quantificação do estoque de biomassa e carbono florestal, inventário florestal, avaliações e coletas de solos.