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Influence of the impact of a rigid rod on the coffee fruits detachment by mechanical vibrations

Influência do impacto de uma haste rígida no destacamento de frutos de café por vibrações mecânicas

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Abstract: Nowadays, the coffee sector has passed by a transition due the lack of labor, which makes manual harvesting unfeasible. The mechanization has been the solution found by the coffee farmers to overcome the problem of lack of labor and also reduce the production costs. The aim of this study was to evaluate the detachment efficiency behavior of the coffee fruits under mechanical vibrations transmitted to the fruit-stem system by impact of a rigid rod, and mechanical vibrations transmitted to the system without the impact. Trials to evaluate the fruits detachment were performed varying the vibration frequency, the ripening stage of the fruits, the number of fruits at the same stem and the way of transmission of the mechanical vibrations to the fruit-stem system. The detachment efficiency of red fruits was higher than green fruits. It was observed an increase of the detachment efficiency associated to the increase the frequency of vibration. Detachment efficiency obtained from mechanical vibrations transmitted due the impact of a rigid rod on fruit-stem system was 19.4% higher than mechanical vibrations transmitted without impact.

Keywords: mechanization, mechanical vibrations, instrumentation

Resumo: Atualmente, a cafeicultura passa por um momento de transição acarretada pela dificuldade em conseguir mão de obra, o que torna a colheita manual inviável. A mecanização vem sendo a saída encontrada pelos produtores para reduzir seus custos de produção. Objetivou-se com este trabalho analisar o comportamento da eficiência de derriça dos frutos do café com a vibração sendo transmitida ao sistema fruto-pedúnculo com o impacto de uma haste rígida ao fruto, e vibração transmitida ao sistema fruto-pedúnculo sem impacto. Foram realizados ensaios de derriça variando a frequência de vibração, o estádio de maturação dos frutos, o número de frutos solidários ao mesmo pedúnculo e a forma de transmissão da vibração ao sistema fruto-pedúnculo. A eficiência de derriça dos frutos cerejas foi superior à dos frutos verdes. Observou-se o aumento da eficiência de derriça na medida em que se aumentou a frequência de vibração. Verificou-se também que a eficiência de derriça obtida com o modo de transmissão da vibração pelo impacto de uma haste rígida ao fruto foi 19,4% maior que com o modo de transmissão da vibração sem impacto ao fruto.

Palavras-chave: mecanização, vibrações mecânicas, instrumentação

Introduction

The coffee sector was always prominent in Brazilian agriculture. The coffee production in 2014 season was estimated at 2.7 million tons. Currently, among the producing states, Minas Gerais ranks first place, accounting for about 50.4% of Brazilian coffee production (IBGE, 2015). According to Souza et al. (2006), coffee harvesting is composed by many operations, in which the fruits detachment can be considered the most complex operation due the quantity of labor and time demanded to perform it. Manual fruits detachment represents around of 75% of the time spent in manual coffee harvesting process.

Coffee has price and market acceptance directly associated with its final quality. Foreign markets have been demanded a quality coffee and the Brazilian product has difficulty to comply with this requirement. However, according Isquierdo et al. (2012), the increase of the productivity and, mainly, the improve of the coffee quality have been sought by the farmers. The selectivity during the coffee harvesting confers a high quality to the product and, consequently, a better price. Although, the fruits detachment operation becomes more costly and complex (Ciro, 2001; Santos et al., 2010a; Santos et al., 2010b). Nowadays, the coffee sector has passed by a transition due the lack of labor, which is becoming the manual harvesting of the coffee unfeasible. For Barbosa et al. (2005), comparing the volume of coffee effectively harvested, a mechanized process using coffee portable harvester machines presents efficiency 64% higher when compared to workers performing the same job manually.

Mechanization of harvesting process can be an important factor to reduce coffee production costs, once the cost reduction is directly related to the level of mechanization employed in harvesting and processing operations (Barbosa et al., 2005; Souza et al., 2006). When performed manually, coffee harvesting can represent up to 60% of the cost of a bag, which is directly associated to the high demand for labor (Oliveira et al., 2007).

The principle employed to perform coffee mechanical harvesting is based on mechanical vibrations. There are on the market since self-propelled harvester machines that carry out all stages of the harvesting process to small coffee portable harvester machines that are used in semi-mechanized processes of harvesting. This type of machinery has the same principle of working, but the machines have different possibilities to drive such as electric, pneumatic, hydraulic or mechanical (Souza et al., 2006).

The process of mechanical harvesting by mechanical vibrations is carried out by the action of rigid rods vibrating, which generate impacts and induce mechanical vibrations to the fruits and branches of the coffee plant. Thus, when it is used vibrational energy to detach the fruits, the association of factors such as frequency and amplitude of vibration are fundamental to perform an effective process (Sessiz & Özcan, 2006; Lang, 2006; Santos et al., 2010a; Santos et al., 2010b).

Factors such as mechanical properties, geometry, architecture plants and mass of fruits and stems influence directly the mechanical harvesting, due to the great variation of these properties in plants (Srivastava et al., 1996). These features make difficult the data acquisition involved in the harvesting process, which makes necessary the perform of experimental controlled trials in the laboratory or the use of mathematical tools to determine them(Láng, 2006; Santos et al.; 2010a; Tinoco et al., 2014; Santos et al., 2015).

Study different parameters and variables of harvesting process is an efficient way to add the necessary knowledge to optimize machinery available on the market, and to establish a knowledge base for new machine designs. The analysis and study of the influence of the impact between rigid rods found in harvesters machines and the coffee fruit-stem system is a subject still little studied, despite this parameter to be of fundamental in coffee harvester machines design. In this context, the aim of this work was to evaluate the detachment efficiency of the coffee fruits subjected to mechanical vibrations transmitted to fruit-stem system directly by the branch and mechanical vibrations generated by impact of a rigid rod on the fruit-stem system.

Material and methods

The study was conducted using coffee plants of the Catuaí Vermelho variety, collected during the harvesting season in Minas Gerais State. Samples were collected in green and red ripening stages. Immediately after the collect of the branches, the material were sent to the laboratory where samples were prepared for execution of the controlled vibration trials. The trials occurred in a lowest interval of time possible after the collect.

From the collected branches, samples of the fruit-stem systems were prepared considering one and two fruits at the same stem, on green and red ripening stages. The length used for the samples was 50 mm. Figure 1 illustrates the prepared samples with two fruits at the same stem, on red ripening stage.

Figure 1. Samples of coffee fruit-stem systems for red ripening stage.

In Figure 2 is shown the system used to perform the vibration vibration trials. The trials were performed using an electromagnetic shaker manufactured by Ling Dynamic Systems (LDS) V406 model. Also, it was employed a signal generator $COMET_{USB}$ made by Dactron and PA100E-CE amplifier. Through a program supplied by Dactron, a sinusoidal signal were produced by $COMET_{USB}$ signal generator, which was amplified by the PA100E-CE amplifier before reaching the electromagnetic shaker. For the system control during the vibration trials, it was used a piezoelectric acceleration transducer, manufactured by PCB Piezotronics, Inc. The acceleration signal measured by the transducer was used control the frequency and amplitude of vibration of the shaker.

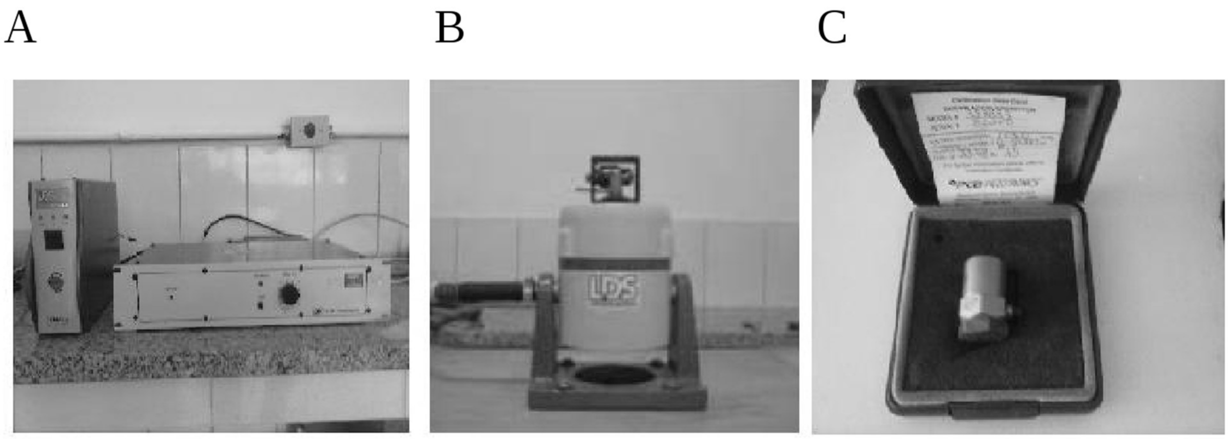

Figure 2. System used in vibration trials: (A) signal generator $COMET_{USB}$ and PA100-CE amplifier, (B) electromagnetic shaker and (C) piezoelectric acceleration transducer employed on system control.

In Table 1 are presented some important technical specifications of the electromagnetic shaker used on vibration trials.

Table 1. Technical specifications of the electromagnetic shaker

Frequency operation range (Hz)	5 – 9000
Maximum load (N)	198
Maximum peak to peak displacement (mm)	17.6
Maximum acceleration (g_n)	100

Coffee samples were fixed to structures specially created for vibration trials. The way of fixation of the coffee samples was associated to vibration transmission: fixation of the samples on mobile base of the electromagnetic shaker (mechanical vibrations transmitted through the sample fixation) and fixation of the samples on a static structure (mechanical vibrations transmitted due the impact of a rigid rod directly on the coffee fruits). Thus, it was developed two fixation structures, as presented in Figure 3. The design of the fixation structures considered the simplicity of working for fixation of the samples during the trials execution.

The structure fixed on the mobile base of the electromagnetic shaker was used to crimp the coffee samples during the vibration trials performed without impact of the rigid rod, in this configuration the vibration signal was transmitted through the fixation structure to the sample (Figure 3A). This structure was also used for the fixation of the rigid rod during the vibration trials performed by using the impact over the coffee fruits (Figure 3B). The static structure allowed the setting of height and the distance of the structure mounted on the mobile base of the electromagnetic shaker.

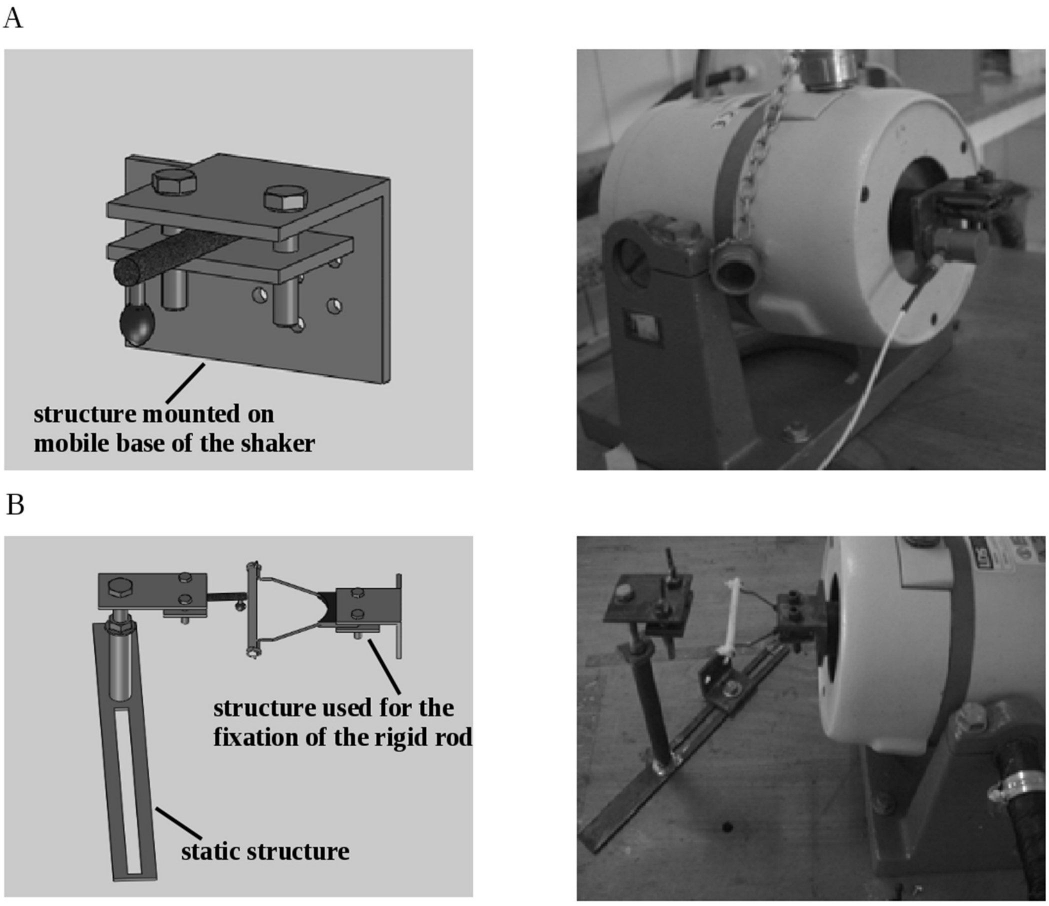

Figure 3. Representation of the two configurations of the vibration trials and its respectively fixation structures: (A) structure mounted on the mobile base of the shaker used on vibration trials without impact and (B) static structure for samples fixation and structure used for fixation of the rigid rod used on vibration trials performed by using impact over the coffee fruits.

In Figure 4 is presented the way of fixation of the coffee samples on the static structure and the rigid rod fixed in a structure mounted on the mobile base of the electromagnetic shaker, this configuration was used on trials in which the main objective was to analyze the mechanical vibration effect generated by the impact of the rod over coffee fruits. Before each trial, the neutral point of the rod displacement was configured for the interface position between the rod and the fruit surface, avoiding the stem deformation.

For the two ways of mechanical vibrations transmission (mechanical vibrations transmitted through the sample fixation and mechanical vibrations transmitted due the impact of a rigid rod directly on the coffee fruits), the electromagnetic shaker was set to carry out the displacement of the shaker mobile base under a sinusoidal function, for the different vibration frequencies employed on trials.

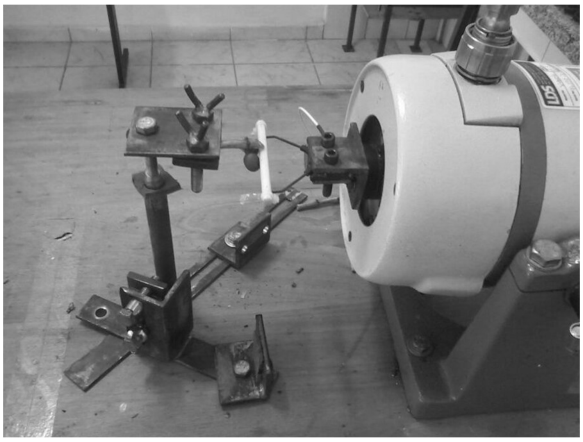

Figure 4. Fixation of the coffee fruit-stem system sample during the trials performed to analyze the effect of the impact of a rigid rod over the fruits.

For the vibration trials, the following factors were considered: two ripening stages of the fruits (green and red; three vibration frequencies (25, 30 and 35 Hz); number of fruits at the same stem (one and two fruits, chosen in order to guarantee the impact would occur directly over the fruits); way of transmission of the mechanical vibrations (mechanical vibrations transmitted, without impact, through the sample fixation and mechanical vibrations transmitted due the impact of a rigid rod directly on the coffee fruits). The vibration trials were perfomed considering a time of vibration of 20 seconds and a peak to peak displacement of the shaker mobile base of 15 mm.

In this study, three trials configurations were evaluated: mechanical vibration transmitted, without impact, through the fixation on shaker of the coffee fruit-stem system (Trial 1); mechanical vibrations transmitted to the coffee fruit-stem system due the impact of a rigid rod (Trial 2); and the evaluation of the different ways of the mechanical vibrations transmission (with and without impact) over the detachment efficiency (Trial 3).

For the Trial 1, the experiment was conducted in a completely randomized design, with three replications, considering a factorial scheme 2 x 3 x 2 with two ripening stages, three vibration frequencies and two configurations of number of fruits at the same stem. On Trial 2, it was employed a completely randomized design, with three replications, considering a factorial scheme 2 x 3 x 2 with two ripening stages, three vibration frequencies and two configurations of number of fruits at the same stem. The difference between trials 1 and 2 was the way of mechanical vibrations transmission. For the Trial 3, it was employed a completely randomized design, with three replications, considering a factorial scheme 2 x 3 x 2 x 2 with two ripening stages, three vibration frequencies, two configurations of number of fruits at the same stem and the way of mechanical vibrations transmission, with or without impact over the coffee fruit-stem system.

The fruit detachment data were submitted to analysis of variance at a 5% significance level. The means of the qualitative factors were studied by Tukey test at a 5% of significance level. The means of the quantitative factors were studied by regression analysis. All of the statistical analyses were performed using R software (R Core Team, 2013).

Results and discussion

The results of the analysis of variance for Trial 1 (mechanical vibration transmitted, without impact, through the fixation on shaker of the coffee fruit-stem system) were not significant at the level of 5% of probability, even the factors frequency and ripening stage, which were observed as significant in coffee fruits detachment by other authors.

Santos et al. (2010a) developed a trial about detachment efficiency under similar conditions of the present trial, the authors observed the frequency of vibration as significant factor from analysis of variance. Though, the frequency range evaluated was larger, varying from 13.33 to 26.67 Hz. The difference between adopted frequency ranges can have contributed for the non significance of this factor, once the adopted frequency range (25 to 35 Hz) is out of resonance of the fruit-stem system (Tinoco et al., 2014; Santos et al., 2015).

It was not observed significant difference for the ripening stage factor considered (green and red). This result

differs from the resultados found other authors (Ciro, 2001; Santos et al. 2010a). However, this behavior can imply that for this way of transmission of the mechanical vibrations, under the conditions of the execution of the trial, there is no possibility to accomplish a selective harvesting using mechanical vibrations.

In Table 2, the results of the analysis of variance of the Trial 2 (mechanical vibrations transmitted to the coffee fruit-stem system due the impact of a rigid rod) is presented. The factors frequency and ripening stage were significant at the level of 5% of probability, similar results were reported by other authors (Ciro, 2001; Santos et al. 2010a; Santos et al. 2010b; Tinoco et al., 2014). The interections among the factors frequency, ripening stage and number of fruits at the same stem were not significant at the level of 5% of probability.

For Trial 2, the factors frequency and ripening stage were significant at a 5% of probability, as presented in Table 2. This behavior was expected, mainly by the frequency factor, once the transferred energy is directly proportional to the frequency magnitude (Ciro, 2001; Santos et al., 2010a).

Table 2. Results of the analysis of variance for the Trial 2 (mechanical vibrations transmitted due the impact of a rigid rod directly on the coffee fruit-stem system)

SV	DF	SS	MS	F	p-value
Frequency (F)	2	6,806.00	3,403.00	3.91^{*}	0.0323
Ripening stage (M)	1	5,625.00	5,625.00	6.46^{*}	0.0171
Number of fruits (NF)	1	69.00	69.00	0.08^{ns}	0.7798
F x M	2	2,917.00	1,458.00	1.68^{ns}	0.2062
NF x M	1	1,736.00	1,736.00	1.99^{ns}	0.1693
NF x F	1	104.00	104.00	0.12^{ns}	0.7321
Residue	27	23,507.00	871.00		
Total	35	40,764.00			

*significant at 5% probability; ^{ns} non-significant.

Equation 1 represents the model selected to study the detachment efficiency from the vibration frequency variation, considering that the mechanical vibrations were transmitted to the coffee fruit-stem system due the impact of a rigid rod.

$$ef = 2.03 f + 21.12 \quad (1)$$

Where: *ef* = detachment efficiency, %; *f* = frequency of vibration, Hz.

In Figure 5 is presented the behavior of the coffee fruits detachament as function of the frequency of vibration. It was observed that the greatest detachment efficiency occurred on vibration frequency of 35 Hz, which is associated to the vibrational energy transmitted to fruit-stem system during the vibration process (Souza et al., 2005; Santos et al. 2010b).

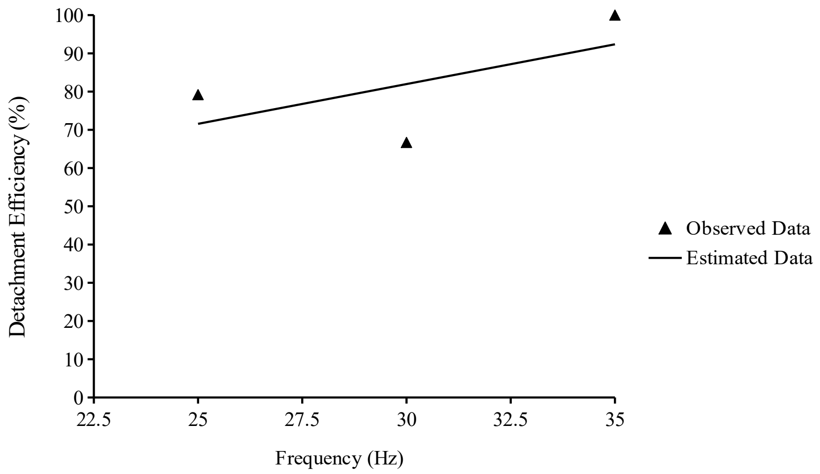

Figure 5. Effect of the frequency of vibration over the detachment efficiency of the coffee fruits obtained from the Trial 2 (mechanical vibrations transmitted to the coffee fruit-stem system due the impact of a rigid rod).

It was observed that the frequency of 25 Hz presented a detachment efficiency higher than frequency of 30 Hz, in spite of the minor vibrational energy transmitted to fruit-stem system. This behavior can be attributed to resonance phenomenon once the frequency of vibration of 25 Hz was near to natural frequency of coffee fruit-stem system (Ciro, 2001; Souza et al., 2005; Tinoco et al., 2014; Santos et al., 2015; Villibor et al., 2016). Using an analytical method, Ciro (2001) determined the first natural frequency of the coffee fruit-stem system of 25.1 and 26.9 Hz for green and red ripening stages, respectively. Other authors, using finite element method, determined the first natural frequency, for green and red ripening stages, varying from 15 to 23 Hz (Tinoco et al., 2014; Santos et al. 2015).

Ripening stage factor was also significant at 5% of probability (Table 2), which can be associated to the lesser forces required to detach the red fruits than green fruits (Souza et al., 2005). Sival et al. (2010) studied the detachment of the coffee fruits using an axial force applied to the fruit-stem system. The authors verified that the green fruits can demanded greatest detachment forces than red fruits, in many cases this force can be up to 73.42% larger. In Figure 6 is presented the effect of ripening stage over the detachment efficiency of the coffee fruits, considering that mechanical vibrations were transmitted to the coffee fruit-stem system due the impact of a rigid rod. It was observed that coffee red fruits tended to present the highest detachment efficiency (Figure 6). This behavior, also verified by Ciro (2001) and Santos et al. (2010a), can be attributed to a minor stiffness of the stem for the ripening stage of the red fruits. The reduction of the stem stiffness is related to degradation of walls cell of the stems due to enzymatic activities (Rodrigues & Ono, 2011).

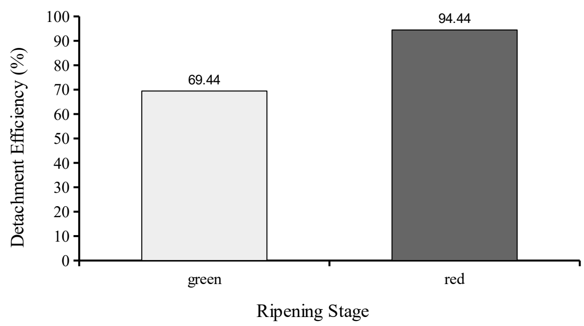

Figure 6. Effect of the ripening stage over the detachment efficiency of the coffee fruits obtained from the Trial 2 (mechanical vibrations transmitted to the coffee fruit-stem system due the impact of a rigid rod).

In Table 3 is presented the results of the analysis of variance for Trial 3 (mechanical vibrations transmission, with and without impact, over the detachment efficiency). The significant factors at 5% of probability were ripening stage and way of transmission of mechanical vibrations.

Though, the interactions among frequency, ripening stage, number of fruits at the same stem and way of transmission of mechanical vibrations were not significant.

Table 3. Results of the analysis of variance for the Trial 3 (mechanical vibrations transmitted with or without impact of a rigid rod on the coffee fruit-stem system)

SV	DF	SS	MS	F	p-value
Frequency (F)	2	4,653.00	2,326.00	1.64^{ns}	0.2032
Ripening stage (M)	1	13,889.00	13,889.00	9.76^{*}	0.0027
Number of fruits (NF)	1	556.00	556.00	0.39^{ns}	0.5343
Transmission (TR)	1	6,806.00	6806	4.78^{*}	0.0325
F x TR	2	5,069.00	2,535.00	1.78^{ns}	0.1768
M x TR	1	139.00	139.00	0.10^{ns}	0.7557
NF x TR	1	139.00	139.00	0.10^{ns}	0.7557
Residue	62	88,194.00	1,422.00		
Total	71	119,445.00			

*significant at 5% probability; ^{ns} non-significant.

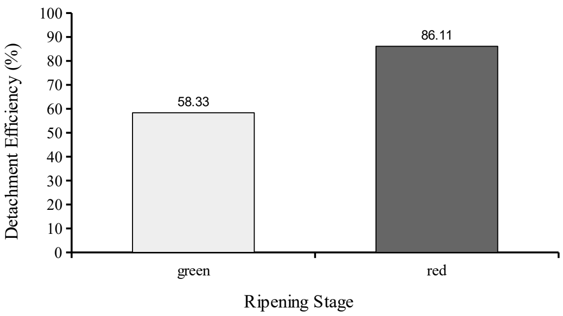

Figure 7. Effect of the ripening stage over the detachment efficiency of the coffee fruits obtained from the Trial 3 (mechanical vibrations transmitted with or without impact of a rigid rod on the coffee fruit-stem system).

In Figure 7 is presented the results for the effect of ripening stage over coffee fruits detachment efficiency obtained from the Trial 3. From the results presented in Figure 7, it was observed the effect of ripening stage influenced directly the coffee detachment efficiency, similar results were obtained from Trial 2 (Figure 2). This behavior suggests that mechanical harvesting could be performed with selectivity, mainly when the harvesting process is carry out by mechanical vibrations generated due the impact of rigid rods on plagiotropic branches of the coffee plants (Silva et al., 2013).

The way of transmission of the mechanical vibrations to coffee fruit-stem system influenced the detachment efficiency of the fruits (Table 3), these results were presented in Figure 8.

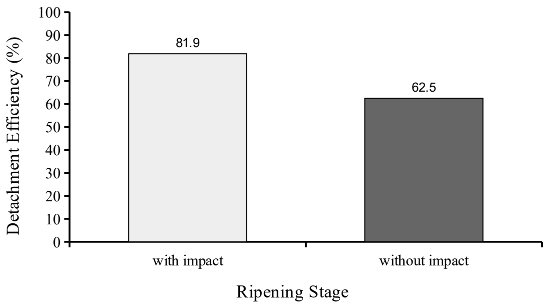

Figure 8. Effect of the mechanical vibrations transmission over the detachment efficiency of the coffee fruits obtained from the Trial 3 (mechanical vibrations transmitted with or without impact of a rigid rod on the coffee fruit-stem system).

It was observed that detachment efficiency is significantly influenced by impact of a rid rod on the coffee fruit-stem system (Silva et al., 2013). This kind of mechanical vibrations transmission presented a detachment efficiency 19.4% higher than the mechanical vibrations transmitted through the fixation of the samples, without the impact of the rigid rod (Figure 8). This behavior is graphically emphasized from the Figure 9.

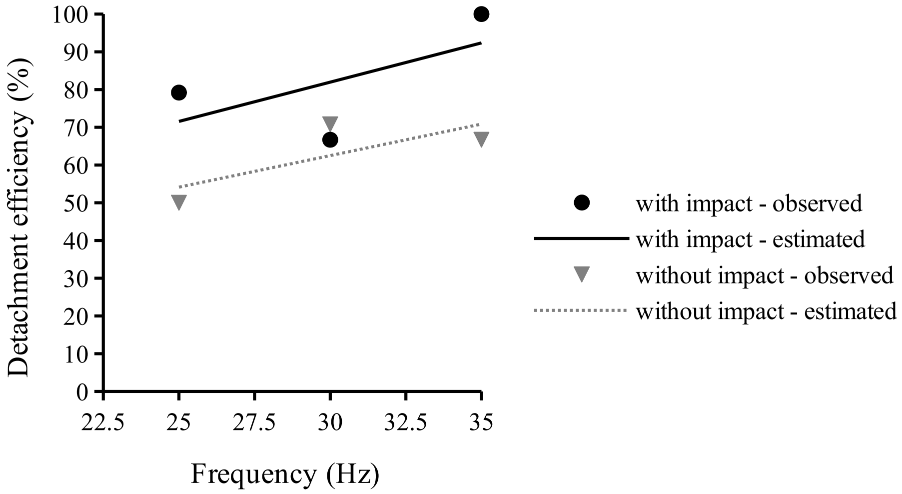

Figure 9. Effect of the mechanical vibrations trasmission, with or without impact, over the detachment efficiency of the coffee fruits.

Mechanical vibrations transmitted to coffee fruit-stem system employing the impact of a rigid rod is characterized by a transfer of vibrational energy in short interval of time. In this situation, there was an effective transmission of energy of the vibration process, resulting in a greatest coffee detachment efficiency. These results emphasizes the importance of the studies carried out for the coffee machinery optimization, specially the harvesting machines which employ the interaction between rigid rods and plagiotropic branches (Ciro, 2001; Souza et al., 2005; Santos et al., 2010a; Silva et al. 2010; Silva et al., 2013).

Conclusion

Of vibration, when associated with the impact, influences directly the detachment efficiency of the coffee fruits. Coffee detachment efficiency increases when the ripening stage advances from green ripening stage to red ripening stage. The way of transmission of the mechanical vibrations influences directly on coffee detachment efficiency. Mechanical vibrations transmitted due the impact of a rigid rod on coffee fruit-stem systems presented a greatest detachment efficiency than mechanical vibrations, without impact, transmitted through the fixation of the stem.

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