



EDUARDO HÉLIO DE NOVAIS MIRANDA

**VALORIZAÇÃO DE RESÍDUOS DE FEIJÃO NA PRODUÇÃO
DE MATERIAIS COMPÓSITOS**

LAVRAS – MG

2025

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia de Biomateriais, área de concentração em Compósitos e Nanocompósitos Lignocelulósicos, para a obtenção do título de Doutor.

D.Sc. José Benedito Guimarães Júnior
Orientador

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2025**

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MATERIALS**

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RESUMO

A produção agrícola de feijão no Brasil é realizada em grande escala. Concomitante à alta produção industrial, há uma grande geração de resíduos. Face a este contexto, este trabalho teve como objetivo analisar o reuso de caules e vagens de feijão (*Phaseolus vulgaris*) na produção de três tipos de materiais compósitos: painéis aglomerados, compósitos de gesso e compósitos poliméricos. Para tanto, os resíduos da cultura de feijão foram primeiramente caracterizados *in natura*. Posteriormente, esses elementos lignocelulósicos foram incorporados nos painéis de madeira, produzidos com adesivo a base de ureia-formaldeído, através de diferentes níveis de substituição em massa (0%, 25%, 50%, 75% e 100%) da madeira de *Pinus oocarpa* por partículas do subproduto. Em compósitos de gesso de relação constante de água:gesso de 0,6, por outro lado, as partículas de resíduo de feijão foram incorporadas a matriz através de diferentes teores de substituição em massa (0%, 2,5%, 5%, 7,5% e 10%) do gesso pelos resíduos. Por fim, partículas de resíduos de feijão também foram incorporadas em compósitos poliméricos através de diferentes teores de substituição em massa (0%, 10%, 20%, 30% e 40%) de polietileno de baixa densidade (PEBD) reciclado por partículas de resíduos de feijão. Os impactos da presença de resíduos de feijão nos compósitos foram analisados a partir do resultado de testes físicos e mecânicos. Os resíduos de feijão apresentaram valores de densidade aparente de 0,24 g/cm³, e de teores de lignina de 8,13%, de holocelulose de 56,55%, de extrativos de 8,16% e de cinzas de 16,94%. Nos painéis aglomerados a incorporação de tais resíduos não influenciou significativamente a densidade aparente nas amostras analisadas. Além disso, houve aumento nas propriedades de razão de compactação, absorção de água e de inchamento em espessura e redução nas propriedades mecânicas proporcionalmente ao maior teor de substituição da madeira de pinus pelos resíduos. Por outro lado, nos compósitos de gesso, houve um aumento no isolamento térmico e acústico nos compósitos com a presença de resíduos de feijão. Além disso, em teores de substituição de até 5,0% de gesso pelo material lignocelulósico, houve uma diminuição da umidade e aumento na maioria das propriedades mecânicas analisadas. Já nos compósitos poliméricos os resultados mostraram que o material lignocelulósico ocasionou uma diminuição da densidade e das propriedades mecânicas e aumento das propriedades de absorção de água após 24 h de imersão e teor de umidade; estes resultados foram correlacionados aos vazios, trincas e pontos concentradores de tensão encontrados nas micrografias realizadas. Além disso, no ensaio de inflamabilidade, os resíduos de feijão contribuíram para uma maior propagação de chamas. Dessarte, a pesquisa apresentou resultados importantes visando a propagação de processos de menor impacto ambiental e geração de produtos de maior valor agregado, principalmente nas indústrias moveleiras, de construção e de materiais pré-moldados como placas, *decks*, brises, dentre outros.

Palavras-Chave: resíduos agrícolas; compósitos de gesso; painéis aglomerados; compósitos poliméricos.

ABSTRACT

Bean agricultural production in Brazil is large-scale. Concomitant with high industrial production, there is a significant generation of waste. Given this context, this study aimed to analyze the use of bean (*Phaseolus vulgaris*) stems and pods in the production of three types of composite materials: agglomerates, gypsum composites, and polymeric composites. To this end, bean crop residues were first characterized in their natural state. Subsequently, these lignocellulosic elements were incorporated into wood panels produced with a urea-formaldehyde adhesive, through different levels of mass replacement (0%, 25%, 50%, 75%, and 100%) of *Pinus oocarpa* wood with particles of the byproduct. In gypsum composites with a constant water:gypsum ratio of 0.6, on the other hand, bean waste particles were embedded in the matrix through different mass substitution rates (0%, 2.5%, 5%, 7.5%, and 10%) of gypsum by waste. Finally, bean waste particles were also incorporated into polymeric composites through different mass substitution rates (0%, 10%, 20%, 30%, and 40%) of recycled low-density polyethylene (LDPE) by bean waste particles. The impacts of the presence of bean waste on the composites were analyzed based on the results of physical and mechanical tests. The bean waste presented an apparent density of 0.24 g/cm³, and lignin contents of 8.13%, holocellulose of 56.55%, extractives of 8.16%, and ash of 16.94%. In particleboards, the incorporation of such residues did not significantly influence the apparent density of the samples demonstrated. Furthermore, there was an increase in compaction ratio, water absorption, and thickness inchange properties, and a reduction in mechanical properties proportionally to the higher pine wood replacement rate by residues. On the other hand, in gypsum composites, there was an increase in thermal and acoustic insulation in composites with the presence of bean residues. Furthermore, in theoretical substitutions of up to 5.0% of gypsum by lignocellulosic material, there was a decrease in moisture content and an increase in most of the proven mechanical properties. In polymeric composites, the results showed that the lignocellulosic material caused a decrease in density and mechanical properties and an increase in water absorption properties after 24 h of experimentation and moisture content; these results were correlated with voids, cracks, and stress concentration points found in the micrographs. Furthermore, in the flammability test, the bean residues developed greater flame propagation. Thus, the research presented important results evolving in the propagation of processes with lower environmental impact and generation of products with higher added value, mainly in furniture, construction, and precast materials industries such as plates, decks, brise-soleils, among others.

Keywords: agricultural waste; gypsum composites; agglomerated panels; polymeric composites.

INDICADORES DE IMPACTO

O objetivo deste trabalho científico foi analisar o efeito da incorporação de resíduos de feijão (caules e vagens) em três materiais compósitos: painéis aglomerados, compósitos de matriz de gesso, e em compósitos poliméricos. Os resultados atingidos impactam diretamente a agroindústria, geradora de resíduos, atendendo ao décimo segundo Objetivo de Desenvolvimento Sustentável (ODS) no Brasil da Organização das Nações Unidas (ONU, 2022) - Consumo e produção responsáveis - através do reuso de produções agrícolas do Brasil, um país economicamente voltado para a produção e exportação de *commodities*, como da cultura de feijão; o projeto também beneficia as indústrias de fabricação de painéis de madeira (moveleira, setor de embalagens e construção civil), de compósitos de gesso (construção civil) e compósitos poliméricos (materiais pré-moldados de placas, *decks*, brises, dentre outros), notadamente conhecidas pelos grandes impactos ambientais gerados em seus processos produtivos, atendendo ao nono ODS da ONU que trata das relações de Indústria, Inovação e Infraestrutura, pois obtém um produto inovador e de maior valor agregado que minimiza impactos ambientais dos processos produtivos convencionais e possibilita uma cadeia produtiva mais sustentável nestas indústrias (Organização das Nações Unidas ONU, 2022). O trabalho se alinha também com os tópicos “Tecnologia e produção” e “Meio Ambiente” da Política Nacional de Extensão (Fórum de Pró-Reitores de Extensão das Instituições Públicas de Educação Superior Brasileiras - FORPROEX, 2012). Destaca-se que os resultados mais promissores foram obtidos nos compósitos de gesso, indicando que processos industriais para sua geração em larga escala devem ser difundidos.

IMPACT INDICATORS

The objective of this scientific study was to analyze the effect of incorporating bean waste (stems and pods) into three composite materials: particleboard, gypsum matrix composites, and polymer composites. The results achieved directly impact the agribusiness industry, which generates waste, and meet the twelfth Sustainable Development Goal (SDG) in Brazil of the United Nations (ONU, 2022) - Responsible consumption and production - through the reuse of agricultural products from Brazil, a country economically focused on the production and export of commodities, such as beans. The project also benefits the wood panel manufacturing industries (furniture, packaging, and construction), gypsum composites (construction), and polymer composites (precast materials for panels, decks, sunshades, among others), which are notorious for the significant environmental impacts generated by their production processes. This industry meets the UN's ninth SDG, which addresses Industry, Innovation, and Infrastructure. It provides an innovative, higher-value product that minimizes the environmental impacts of conventional production processes and enables a more sustainable supply chain in these industries (ONU, 2022). The work is also aligned with the topics “Technology and Production” and “Environment” of the National Extension Policy (Fórum de Pró-Reitores de Extensão das Instituições Públicas de Educação Superior Brasileiras - FORPROEX, 2012). It is noteworthy that the most promising results were obtained with gypsum composites, indicating that industrial processes for their large-scale production should be disseminated.

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PRIMEIRA PARTE

1 INTRODUÇÃO

De acordo com a Companhia Nacional de Abastecimento - CONAB (2025), há uma estimativa de produção para a safra de grãos brasileira do período 2024/2025 de cerca de 340 milhões de toneladas. Em face dessa alta produção agrícola no Brasil, como a partir do cultivo de feijão, a sexta cultura de grãos mais produzida no país, são gerados uma grande quantidade de resíduos como caroços, bagaços, cascas e outras sobras do processamento. Estudos que visam o reuso de tais materiais em materiais compósitos, neste contexto, são importantes, visando a promoção de uma economia circular no país.

Os painéis aglomerados, um dos compósitos com potencial de reaproveitamento de resíduos, nesta perspectiva, são obtidos pela redução de madeira ou materiais lignocelulósicos em partículas que, após secas e coladas com adesivo sintético, são conformadas pela ação do calor e da pressão. Tais produtos são muito utilizados, por exemplo, pela indústria moveleira e processos sustentáveis produtivos visando principalmente o menor custo deste material, substituindo a madeira por resíduos, vêm sendo analisados (ABNT NBR 14810-1, 2013; Guimarães Júnior *et al.*, 2016).

Já os compósitos de gesso, mineral aglutinante produzido pelo aquecimento da gipsita, são amplamente utilizados na construção civil em acabamentos internos, forros, placas e outros elementos pré-moldados, como em *drywall*; entretanto, esses materiais possuem baixa resistência à tração e à flexão, alta permeabilidade à água, alta porosidade e também geram grande impacto ambiental durante seu processo de produção; por isso alternativas sustentáveis vêm sendo estudadas (Kuqo; Mai, 2021).

Estudos a partir compósitos poliméricos conformados por processos de pressão e calor em materiais pré-moldados de uso em pergolados, *decks*, móveis, itens de decoração, brises, rodapés e materiais para a indústria automotiva também vêm sendo analisados visando a redução de custos destes produtos e aperfeiçoamento de suas propriedades físico-mecânicas a partir da incorporação de materiais residuais (Chaudemanche *et al.*, 2018).

A utilização de resíduos agrícolas em diferentes matrizes está sendo estudada, portanto, por pesquisadores em diversas matrizes. Dentre os estudos já publicados, têm-se a combinação de resíduos agrícolas como de videria (Wong *et al.*, 2020), de algodão (Son *et al.*, 2017), do bagaço de cana-de-açúcar (Soares *et al.*, 2017) e de café (Scatolino *et al.*, 2017) em painéis particulados. Resíduos de trigo (Gomes *et al.*, 2022), de cacau (Veloso *et al.*, 2021), de arroz (Selamat *et al.*, 2019), de abacá (Iucolano *et al.*, 2015) e de outras culturas também foram

analisados em conjunto a matrizes de gesso. Compósitos poliméricos com incorporação de alguns resíduos vegetais, como de bambu (Gomes *et al.*, 2021), de bagaço de cana (Madhoushi *et al.*, 2021), de abacaxi (Dilli Babu *et al.*, 2020) e de pseudocaule de banana (Jordan; Chester, 2017), também foram investigados. Os resultados dessas pesquisas vêm demonstrando, em geral, menor resistência dos compósitos a ambientes úmidos e propriedades mecânicas reduzidas em comparação com os compósitos tradicionais, mas que até determinados níveis de substituição, atendem satisfatoriamente aos requisitos das normas técnicas vigentes.

Dentre os resíduos agrícolas ainda pouco explorados nessas matrizes, porém, destacam-se os subprodutos do feijão, cultura de relevância global que gera uma grande quantidade de resíduos como vagens, ramas, caules, folhas e raízes. O reaproveitamento destes resíduos na produção de compósitos como substitutos parciais/totais ou aditivos normatizados atende às demandas de sustentabilidade e de popularização requeridas pela atual sociedade (Kanning *et al.*, 2014). Dentre as vantagens desta prática, destaca-se a minimização de impactos ambientais, ampliação de oferta de matéria prima, redução do volume de rejeitos descartados no meio ambiente e contribuições para a substituição parcial de matérias-primas virgens e para o aumento da eficiência na produção gerando produtos de maior valor agregado.

Diante desse cenário, o objetivo deste trabalho é analisar o efeito da incorporação de resíduos de feijão (caules e vagens) em três materiais compósitos: painéis aglomerados, compósitos de matriz de gesso, e em compósitos poliméricos.

2 OBJETIVOS

O objetivo deste estudo é analisar o efeito da presença de partículas de caules e vagens de feijão nas propriedades físicas, mecânicas e microestruturais de três materiais compósitos:

1. Painéis de madeira, confeccionados a partir de adesivo à base de ureia-formaldeído, com diferentes níveis de substituição em massa (0%; 25%; 50%; 75%, e 100%) da madeira de *Pinus oocarpa* por partículas do resíduo;
2. Compósitos de gesso de relação água:gesso fixa em 0,60, com substituição parcial do gesso pelo resíduo de feijão em diferentes teores (0%, 2,5%, 5%, 7,5% e 10%) em massa;
3. Em compósitos poliméricos através de diferentes teores de substituição em massa (0%, 10%, 20%, 30% e 40%) do polietileno de baixa densidade (PEBD) reciclado por partículas de resíduos de feijão.

3 ORGANIZAÇÃO DA TESE

Esta tese será organizada em três partes. A ordem de apresentação e o conteúdo abordado em cada capítulo são consecutivamente:

- **1ª parte - Introdução, Organização da Tese e Referencial Teórico:** Esta primeira seção apresenta a introdução da tese, as contribuições da pesquisa, os objetivos principais do estudo, além das principais pesquisas recentes desenvolvidas sobre o tema encontradas na literatura;
- **2ª parte - Artigos:** Na segunda parte da tese serão apresentados os três artigos resultantes do trabalho desenvolvido:
 - **Artigo 1 - Avaliação de resíduos de feijão na produção de painéis aglomerados:** Este artigo analisa as propriedades físico-mecânicas de painéis aglomerados de madeira de *Pinus oocarpa* produzidos com diferentes níveis de substituição da madeira por resíduos de feijão (0%, 25%, 50%, 75% e 100%).
 - **Artigo 2 - Avaliação da influência da adição de resíduos de feijão em matrizes de gesso:** Será apresentado o segundo artigo desenvolvido, cujo objetivo foi verificar o efeito de diferentes níveis de substituição em massa (0%, 2,5%, 5%, 7,5% e 10%) do gesso por partículas de resíduo de feijão nas propriedades físico-mecânicas de compósitos com relação água:gesso constante de 0,60.
 - **Artigo 3 - Valorização de resíduos agrícolas de feijão para produção de compósitos poliméricos:** Nesta terceira seção da segunda parte será apresentado o último artigo desenvolvido em que o objetivo foi avaliar as propriedades físico-mecânicas de compósitos de matriz de polietileno de baixa densidade (LDPE) nos quais partículas de resíduos de feijão foram introduzidas em diferentes níveis de substituição em massa em relação ao polímero (0%, 10%, 20%, 30% e 40%).
- **3ª parte - Considerações finais e Referências:** Na terceira parte da tese estão descritas as considerações finais do estudo acompanhadas das referências que fundamentaram a pesquisa.

4 REFERENCIAL TEÓRICO

4.1 Produção e consumo do feijão no Brasil

O Brasil é um dos países que mais se destaca no mundo quanto ao cultivo de culturas agrícolas. Dentre as culturas de grãos que mais contribuem para esses números elevados, está o feijão (Figura 1), vegetal da família das *Fabaceas* (subfamília *Faboidae*) que tem como característica marcante o desenvolvimento de frutos do tipo legume, também conhecido como vagem.

Figura 1 - Mudanças para a produção de feijão.



Fonte: Oliveira (2022).

Várias são as explicações para origem e domesticação da cultura de feijão no continente americano. Algumas evidências demonstraram que a planta teria sido domesticada na Mesoamérica, por volta de 7000 a.C., e, posteriormente, disseminada pela América do Sul. Outra hipótese, baseada em achados arqueológicos de 10.000 anos a.C., concluiu que a origem da planta e sua domesticação ocorreram na própria América do Sul, mais especificamente no Peru, e, somente depois, tal cultura foi disseminada para a América do Norte (Vasconcelos, 2011).

No Brasil, o feijão já era consumido no território, cozido através de panelas de barro, pelos povos indígenas habitantes da região. Durante muitos séculos, mesmo com a colonização realizada pelos portugueses, o grão não foi popularizado na Europa por questões de não aceitação do paladar por parte dos europeus. Mesmo assim, essa leguminosa já era comercializada em feiras de escambo na cidade de Salvador, Bahia. Tal cultura agrícola era, na época, oferecida seca ou em vagem pelas famílias indígenas produtoras (Ferreira; Barrigossi, 2021).

Por meio do convívio entre os diferentes povos que formaram o país, a culinária associada ao feijão também foi se diversificando através de caldos, temperos, pimentas e carnes. A diversidade dentre as regiões também possibilitou diferentes formas de preparo do alimento (Ferreira; Barrigossi, 2021).

Desde o final do século 19, o consumo do grão se tornou mais frequente, fazendo parte da dieta básica das famílias brasileiras. A produção, ainda assim, era feita em pequena escala em hortas domésticas ou em sítios por pequenos produtores familiares. Gradativamente, com a miscigenação e com a criação de diversas versões de preparo, o feijão foi se tornando mais presente na alimentação cotidiana nacional e foi cada vez mais cultivado (Ferreira; Barrigossi, 2021).

Atualmente, o feijão é uma das principais fontes de nutrientes na alimentação dos habitantes brasileiros. Além de carboidratos, tal leguminosa é rica em outros nutrientes essenciais como proteínas, ferro, cálcio, vitaminas (principalmente do complexo B) e fibras, formando, em conjunto com o arroz, um ótimo balanço nutricional. Com média de consumo de 17,7kg/brasileiro/ano, tal cultura agrícola se faz cotidianamente presente no cardápio de cerca de 60 % da população (Vasconcelos, 2011).

A espécie de feijão *Phaseolus vulgaris* (Figura 2), o feijão-comum, mais produzida no Brasil, possui neste contexto, cultivo distribuído em três safras anuais: a safra das águas, a da seca e a do outono-inverno, com destaque, como citado anteriormente, na dieta alimentar e na geração de receitas para produtores (CONAB, 2025).

Figura 2 - Grãos de feijão da espécie *Phaseolus vulgaris*.



Fonte: Tobaldini (2015).

De acordo com a Companhia Nacional de Abastecimento - CONAB (2025), a estimativa de produção para a safra de grãos 2024/2025 é de cerca de 340 milhões de toneladas, sendo que o feijão ocupa a sexta posição dentre as culturas de grãos com maior produção.

4.2 Resíduos da cultura de feijão

Concomitante à alta produção de feijão no Brasil, observa-se uma grande geração de resíduos agrícolas provenientes de vagens, ramas, caules, folhas, raízes (Figura 3), advindos dessa cultura agrícola.

Figura 3 - Resíduos secos da colheita de feijão da espécie *Phaseolus vulgaris*.



Fonte: Dos autores (2021).

Diante da alta geração de resíduos, estudos vêm sendo desenvolvidos visando um reuso desses materiais. Dois estudos já publicados demonstraram a eficiência que esses resíduos, gerados na agroindústria, possuem na alimentação de ruminantes ao contribuir para o melhoramento do processo digestivos desses animais (Fuma *et al.*, 2012; Ngwe *et al.*, 2012).

Em outra pesquisa, autores objetivaram analisar o efeito da adição de resíduos de feijão comum - cuja composição química está detalhada na Tabela 1 - sobre as propriedades fermentativas e de qualidade nutricional durante o processo de ensilagem de cana-de-açúcar. Os resultados demonstraram que a inclusão de níveis de até 150 g/kg aperfeiçoou a qualidade dos produtos obtidos, pois reduziu as perdas gasosas, melhorou a composição química e a digestibilidade, sem comprometer o pH das silagens (dos Santos *et al.*, 2018).

Tabela 1 - Propriedades dos resíduos comuns de feijão.

Propriedade	Resultado
Cinzas (%)	55,80
Extrato de éter (g/kg)	14,80
Hemicelulose (%)	58,00
Matéria seca (g/kg)	896,20

Fonte: dos Santos *et al.* (2018)

A avaliação do efeito da substituição do farelo de soja pelo resíduo de feijão comum em rações para vacas em lactação também foi realizada previamente. Os resultados demonstraram não haver diferença significativa de eficiência entre os tratamentos para alimentação; contudo, houve redução da produção e da composição do leite e redução no desempenho dos animais (Magalhães *et al.*, 2008).

Em outro estudo investigou-se o efeito da presença de resíduo de feijão e de milho sobre a estrutura da comunidade bacteriana em solo cultivado de maneira convencional (CB) e sob um sistema de agricultura de conservação (PB). Verificou-se que as práticas agrícolas tiveram um efeito significativo na estrutura da comunidade bacteriana e que os resíduos do feijoeiro foram degradados principalmente por *Bacillus*, *Micrococcaceae* e *Streptomyces* (Ortiz-Cornejo *et al.*, 2017).

Com relação a área de compósitos, poucas pesquisas foram encontradas. Em uma delas, objetivou-se substituir, em painéis aglomerados, a resina a base de ureia-formaldeído para cardanol-formaldeído, e também a madeira de pinus por resíduos de feijão. Os resultados demonstraram que o cardanol-formaldeído proporcionou uma melhora mecânica aos painéis, apresentando maior módulo de elasticidade (MOE) (1172 MPa) e módulo de ruptura (MOR) (4,39 MPa) em relação aos painéis aglutinados com adesivos à base de ureia-formaldeído que apresentaram MOE de 764 MPa e MOR de 2,45 MPa. Além disso, o adesivo natural promoveu redução de 93 % na emissão de formaldeído. Já os resíduos de feijão, em adições de até 15 %, proporcionaram uniformidade de propriedades de umidade e densidade aparente, aumento na razão de compactação e inchamento espessura e diminuição nas propriedades mecânicas analisadas (Faria *et al.*, 2023).

Compósitos híbridos de epóxi também já foram preparados utilizando adição constante em massa de 3 % de resíduos de feijão e adições variadas em massa de caulim calcinado (0,5-5,0 %). As análises de difração de raios-X (DRX) e microscopia eletrônica de varredura (MEV) demonstraram uma dispersão uniforme dos materiais adicionados na matriz de resina epóxi, revelando uma boa interface e compatibilidade. A resistência à tração do compósito híbrido com adição de 2 % de caulim (39,8 MPa) foi a maior dentre os tratamentos realizados. Já a sorção de água dos compósitos híbridos diminuiu efetivamente até 0,87 %, com uma quantidade crescente de caulim. Além disso, os compósitos exibiram uma maior resistência à corrosão a soluções alcalinas e salgadas em comparação com reagentes ácidos. Desse modo, tais compósitos proporcionaram melhora na resistência à tração e à corrosão e na captação de água (Kaya; Yilmaz; Deveci, 2018).

A maioria das pesquisas relacionadas ao reaproveitamento dos resíduos da cultura de feijão, porém, se encontra nas áreas de ciências agrárias e de zootecnia. Pesquisas sobre o efeito da adição de resíduos de feijão e de outros subprodutos nas propriedades físicas e mecânicas de diferentes compósitos ainda são, portanto, incipientes e precisam ser mais desenvolvidas para verificar a viabilidade do uso desses resíduos agrícolas em diferentes setores industriais visando popularização, aperfeiçoamento de propriedades físico-mecânicas e geração de produtos de maior valor agregado para produção industrial.

4.3 Compósitos com potencial de produção a partir de resíduos agroindustriais

4.3.1 Painéis aglomerados

Uma grande quantidade de painéis de madeira é utilizada no mundo. De acordo com a Indústria Brasileira de Árvores (IBÁ, 2024), por exemplo, a produção de painéis de madeira no Brasil no ano de 2023 foi cerca de 8,1 milhões de metros cúbicos. A China lidera a produção mundial respondendo por cerca de 37 % da produção dos painéis de madeira comercializados no mundo enquanto que o Brasil é o nono maior produtor. Dessa produção no país, cerca de 88 % são destinadas para o mercado interno.

Dentre os diferentes tipos de painéis de madeira existentes estão os aglomerados (Figura 4), obtidos pela redução de madeira ou outros materiais lignocelulósicos em partículas que, após secagem e aglutinação natural com adesivo natural ou sintético à base de ureia-formaldeído, melanina-formaldeído, fenol-formaldeído, resorcinol, dentre outros, são conformados pela ação do calor e da pressão (ABNT NBR 14810-1, 2013; Guimarães Júnior *et al.*, 2016).

Figura 4 - Painel aglomerado produzido com resíduos agrícolas de feijão e madeira de pinus.



Fonte: Dos autores (2021).

As espécies de madeira de *Pinus oocarpa* e *Eucalyptus grandis* permanecem como as mais utilizadas como matérias-primas de fabricação para os painéis de madeira e consequentemente em painéis aglomerados. Cerca de 95 % dos mais de 10 milhões de hectares de florestas plantadas no Brasil são compostos por mudas de pinus e eucalipto; desse total, 1,9 milhão de hectares corresponde a florestas de pinus, concentradas principalmente, nas regiões Sul e Sudeste (Indústria Brasileira de Árvores - IBÁ, 2024).

A utilização destas matérias-primas, entretanto, vem sofrendo nos últimos anos, rigorosas fiscalizações quanto ao corte; consequentemente elevando o custo do material. Desse modo, embora não seja o constituinte mais caro dos painéis, uma das formas de promover maior acessibilidade ao público, inclusive democratizando o acesso em locais onde não possuem florestas plantadas, se dá pela substituição parcial ou total destas espécies por alternativas mais baratas e acessíveis. Nesse sentido, as indústrias do setor têm buscado constante inovações e tecnologias, a fim de possibilitar o desenvolvimento desses novos produtos.

Vários resíduos agrícolas têm sido, nesta perspectiva, avaliados quanto à influência de sua adição em painéis particulados, como: o da videira (Wong *et al.*, 2020), de algodão (Son *et al.*, 2017), do bagaço de cana-de-açúcar (Soares *et al.*, 2017), de café (Scatolino *et al.*, 2017), de arroz (Ayrimis; Kwon; Han, 2012), de coco (Narciso *et al.*, 2020), dentre outros.

Os resultados vêm demonstrando, em geral, menor resistência dos painéis a ambientes úmidos e propriedades mecânicas reduzidas em comparação com os tradicionais, mas que até determinados níveis de substituição, atendem satisfatoriamente aos requisitos das normas técnicas vigentes para painéis aglomerados.

4.3.2 Compósitos à base de gesso

A construção civil, responsável por cerca de 21% do consumo de energia e 6,8% das emissões de gases intensificadores do efeito estufa do mundo, é outra indústria que vem sofrendo mudanças visando acompanhar as novas demandas da sociedade. O gesso é um de seus produtos mais produzidos (Yu *et al.*, 2020). Este material aglutinante possui especificações abordadas na norma EN 14496 (CEN, 2017).

O processo de obtenção do gesso ocorre por meio de quatro etapas: extração do gipso, preparação para calcinação, calcinação e seleção. O gipso é uma rocha sedimentar composta por gipsita, anidrita e algumas impurezas, geralmente como argilominerais, calcita, dolomita e material orgânico (Barbosa; Ferraz; Santos, 2014)

A gipsita é a matéria-prima básica do gesso e se caracteriza como um mineral compacto de baixa dureza e solubilidade. Após a extração, a gipsita passa por alguns processos de beneficiamento, britagem, moagem grossa, estocagem, secagem, moagem fina e acondicionamento para adequação ao tipo de forno onde será calcinada em uma faixa de temperatura de 140 °C a 160 °C. Em todos estes processos há liberação de gases poluentes e outros impactos ambientais como de poluição da água, poluição sonora e subsidência do terreno de extração (Yu *et al.*, 2020).

Os compósitos formados por este material (Figura 5), entretanto, são amplamente utilizados na construção civil em acabamentos internos, forros, placas e outros elementos pré-moldados, como em *drywall* (Vimmrová *et al.*, 2011).

Figura 5 - Compósito de gesso reforçado com partículas de resíduos de feijão.



Fonte: Dos autores (2022).

Dentre as vantagens apresentadas por tais materiais, destacam-se o fácil método de preparo, a alta relação custo-benefício, a trabalhabilidade, o bom isolamento térmico, o bom acabamento (devido sua superfície menos rugosa), a resistência ao fogo, a baixa retração por secagem, e em alguns casos, capacidade de regular a umidade no interior das habitações (Vimmrová *et al.*, 2011).

Contudo, esses materiais apresentam limitações como baixa resistência à tração e à flexão, alta permeabilidade à água e alta porosidade. Estas desvantagens podem ser fatores limitantes na utilização do gesso, uma vez que em algumas de suas aplicações são necessárias propriedades mecânicas e físicas superiores às apresentadas pelo material; especificamente o baixo rendimento em contato com a água limita, por exemplo, a aplicação deste produto a locais que não possuam contato com este líquido. A maioria dos processos produtivos da indústria da construção relacionados principalmente à geração de compósitos, como o gesso, também impactam severamente o meio ambiente, causando contaminação do solo e das águas subterrâneas, como mencionado anteriormente (Kuqo; Mai, 2021).

Portanto, a indústria da construção civil está em constante busca pelo desenvolvimento de materiais com menor inserção de matérias-primas primárias, menor impacto ambiental, mais econômicos, duráveis e com melhores propriedades físico-mecânicas. A incorporação de partículas de fibras vegetais como reforço no gesso pode ser, neste contexto, uma alternativa para melhorar suas propriedades físico-mecânicas e diminuir os impactos ambientais associados a produção de gesso. Os materiais reforçados com fibra também podem aperfeiçoar propriedades de dissipação de energia, rigidez, ductilidade e resistência ao impacto (Oliveira *et al.*, 2020; Villela *et al.*, 2020).

Levando isso em consideração, uma grande variedade de reforços vegetais de natureza renovável, biodegradável, de baixa densidade, baixo custo e de boa interação com a matriz foi testada. Resíduos de trigo (Gomes *et al.*, 2022), de cacau (Veloze *et al.*, 2021), de arroz (Selamat *et al.*, 2019) e de abacá (Iucolano *et al.*, 2015) e de outras culturas, por exemplo, foram analisados em conjunto com matrizes de gesso. Os resultados dessas pesquisas indicaram melhorias nas propriedades mecânicas e de isolamento térmico; porém, esses subprodutos tornaram os compósitos mais higroscópicos por possuírem uma grande quantidade de estruturas hidrofílicas como a holocelulose.

4.3.3 Compósitos poliméricos

O uso de materiais poliméricos, principalmente os descartáveis, foi mais acentuado em função da pandemia de COVID-19; conseqüentemente, os resíduos também aumentaram. Entre os anos de 1950 e 2015 foram produzidos aproximadamente 8,3 bilhões de toneladas métricas de plástico virgem; além disso, até o ano de 2050, 12 bilhões de toneladas métricas de resíduos de plástico possuem projeção de descarte em aterros sanitários e ambientes naturais (Geyer; Jambeck; Law, 2017). Os setores que mais utilizam materiais plásticos são a construção civil (19 %) e o setor de embalagens (42 %) (Acuña-Pizano *et al.*, 2022).

O descarte inadequado desses materiais causa poluição ambiental, principalmente em leitos de rios e oceanos. Portanto, há necessidade de diminuir a produção e o uso de produtos não renováveis ou, no mínimo, promover uma maior reciclagem desses materiais. O Brasil, por exemplo, foi responsável pela geração de 11,30 milhões de toneladas de resíduos poliméricos em 2016 e apenas 1,28 % desse total de polímeros foi reciclado (Kaza *et al.*, 2018). Nesse contexto, o uso de materiais poliméricos reciclados é uma alternativa potencial para reduzir os impactos ambientais, economizar energia, preservar fontes não renováveis, e reduzir custos nos novos produtos poliméricos (Thomas *et al.*, 2022).

O reuso destes poliméricos reciclados em compósitos, como em conjunto com madeira surge como alternativa também ao grande tempo de decomposição destes materiais plásticos (450 a 500 anos). O desenvolvimento destes materiais multifásicos vem crescendo nos últimos dez anos em diversos setores da economia mundial. A América do Norte, China e a Europa foram os três polos de maior produção destes produtos. Na China, por exemplo, a produção de peças de compósitos poliméricos triplicou entre 2010 e 2012. Alguns materiais produzidos a partir desses componentes são os pergolados, *decks*, móveis, itens de decoração, brises, rodapés, materiais para a indústria automotiva, etc (Chaudemanche *et al.*, 2018).

Uma das matérias-primas utilizadas para a produção de compósitos poliméricos é o polietileno de baixa densidade (PEBD). Este é considerado um material de alta relação resistência / densidade, de grande resistência química, grande tenacidade, alta resistência ao impacto e boa processabilidade (Jordan; Chester, 2017). Outras propriedades físico-mecânicas do PEBD são apresentadas na Tabela 2.

Tabela 2 - Propriedades do PEBD.

Propriedade	Resultado
Densidade (g/cm ³)	0,912 - 0,925
Temperatura de fusão (°C)	102 - 112
Tração no escoamento (MPa)	6,20 - 11,50
Alongamento no escoamento (%)	100 - 800
Resistência à tração (MPa)	6,9 - 16,0
Módulo de elasticidade (MPa)	102 - 240
Dureza (Shore D)	40 - 50

Fonte: Coutinho, Mello, de Santa Maria (2003).

Entretanto, por não ser biodegradável, se descartado de forma ambientalmente incorreta, pode causar impactos devido sua acumulação, prejudicando o ecossistema durante suas centenas de anos de degradação. Seu aproveitamento e valorização em estado reciclado possibilitam a redução desses impactos (Kazemi; Fini, 2022).

Em relação à matéria-prima vegetal para a produção desses compósitos, a fibra da madeira é o principal componente utilizado para esse fim, devido às suas características favoráveis como a baixa densidade e alta resistência (Ayrilmis; Kwon; Han, 2012). No entanto, entende-se que qualquer material lignocelulósico pode estar apto a ser incorporado em matrizes poliméricas para produção de compósitos (Bhaskar *et al.*, 2021). Dessa forma, torna-se

interessante verificar outras fontes viáveis para utilização, a fim de ampliar a oferta de matéria prima, diminuir custos, a demanda por grandes plantações de árvores e aperfeiçoar as características físico-mecânicas dos materiais obtidos.

Uma opção econômica que vem sendo estudada é a utilização desses materiais poliméricos em conjunto com resíduos lignocelulósicos agrícolas (Figura 6), ou seja, produtos fabricados por moldagem por injeção ou extrusão-descarte de polímeros termoplásticos granulares descontínuos com adição de fibras vegetais advindas de resíduos das culturas agrícolas (Brenken *et al.*, 2019). Tais inserções poderiam resolver dois problemas apresentados por esses materiais “*in natura*”: a baixa rigidez de alguns polímeros e a alta absorção de água encontrada na maioria das fibras vegetais (Mertens; Gurr; Krause, 2017).

Figura 6 - Pellets de PEBD e resíduos de feijão para produção de madeira polimérica.



Fonte: Dos autores (2023).

Há relatos na literatura de pesquisadores, que obtiveram êxito ao trabalharem com resíduos agrícolas como bambu (Gomes *et al.*, 2021), bagaço de cana (Madhoushi *et al.*, 2021),

abacaxi (Dilli Babu *et al.*, 2020) e pseudocaule de banana (Jordan; Chester, 2017) associados a matrizes poliméricas.

SEGUNDA PARTE**ARTIGO 1 - Avaliação de resíduos de feijão na produção de painéis aglomerados**

Artigo 1 - Redigido conforme norma do periódico científico - Versão publicada	
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**EVALUATION OF BEAN RESIDUES IN THE PRODUCTION OF
AGGLOMERATED PANELS**

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ABSTRACT

This work aimed to evaluate the physical-mechanical properties of *Pinus oocarpa* wood agglomerated panels produced with different levels (0 %, 25 %, 50 %, 75 % and 100 %) of wood replacement with bean residues. For this purpose, *Pinus oocarpa* wood and the agricultural residue were reduced into particles and their properties of apparent density, extractives, lignin and ash content of these raw materials were determined. Then, the particles were dried to a 3 % humidity and granulometrically selected to produce panels with a density of 0,60 g/cm³. These particles were bonded using 12 % urea-formaldehyde adhesive, pressed, following normative dimensions (250 mm x 250 mm x 15 mm (width, length, and thickness)), and kept in a climate-controlled environment (20 °C ± 2 °C and 65 % ± 5 % RH) until the physical and mechanical tests were carried out. The research results indicated that the particles from bean residues in comparison with *Pinus oocarpa* wood, presented low density, lignin and holocellulose values, and higher extractives data. Furthermore, regarding the characterization of the panels, there was a trend towards uniformity in the apparent density values, an increase in the properties of compact ratio, water absorption and thickness swelling, and a decrease in their mechanical properties associated with the increase in the by-product addition to the panels. Therefore, new studies are necessary, seeking a larger study and greater knowledge of the addition effects of bean residues in particulate panels, aiming the dissemination of this sustainable process on large scale.

Keywords: Agglomerates, urea-formaldehyde, *Pinus oocarpa*, agricultural residues, sustainability.

INTRODUCTION

Agglomerated sheet panels are obtained by reducing wood or lignocellulosic materials into particles, which, after being dried and bonded employing synthetic adhesive, are formed through the action of heat and pressure (ABNT NBR 14810- 1 (ABNT 2013)).

Such products stand out among wood-based goods and are considered the most consumed materials worldwide in this field. In this sense, panel industries are characterized by a constant search for innovation and technology, which favors the development of new and sustainable production processes, mainly aimed at popularizing this material. Wood species, such as the *Pinus oocarpa*, present medium hardness, high strength and other desirable physical-mechanical properties, mainly for the furniture industry, however, and even though it is not the most expensive raw material, one of the ways of greater accessibility to the public is through their replacement by cheaper products.

In this context and in view of the current great social demand for the diffusion of economic and ecological processes in the different branches of human activities, several agricultural residues have been evaluated regarding the influence of their addition in particulate panels, such as soybean (Borges *et al.* 2022), grape (Wong *et al.* 2020), cotton (Nguyen *et al.* 2020), corn (Prasetiyo *et al.* 2020), sugarcane bagasse (Soares *et al.* 2017), hazelnut (Çöpür *et al.* 2007), coffee (Scatolino *et al.* 2017, Santos *et al.* 2022), rice (Ayrilmis *et al.* 2012), coconut (Narciso *et al.* 2020). Particles of wheat (Gomes *et al.* 2023), bamboo (Gomes *et al.* 2021, Miranda *et al.* 2022) and bean (Miranda *et al.* 2023) were also evaluated in matrices of other composite materials of gypsum, cement and polymer.

Bean residues emerge among the mentioned crops as they are highly produced in Brazil and worldwide; for example, the 2020/2021 Brazilian crop production projections reach

2,86 million tons of edible beans. From which its residues, pods, vines, stalks, leaves, roots, etc., were estimated at 1,43 million tons (CONAB 2020).

Studies found in literature argued that these residues generated from the agroindustry can be reused in improving the digestion of ruminants (Fuma *et al.* 2012, Ngwe *et al.* 2012). Though, researches on the addition effect of bean residues on the physical and mechanical properties of reconstituted wood panels are still incipient and, needs to be further developed to verify the feasibility of using agricultural residues in this industrial sector. The use of these residues in wooden panels would meet the sustainability requirements of today's society in the panel industry, with the popularization of these products, and in the agricultural industry, with the reuse of underutilized waste.

Hence the objective of this project is the evaluation of the physical-mechanical properties of particulate panels with the replacement of *Pinus oocarpa* wood by bean crop residues.

MATERIAL AND METHODS

Experimental

The bean residues used in the experiment, stems and pods, came from the harvest remains of the bean *Phaseolus vulgaris* species. The material was obtained from the Pimentas farm (Lavras, Minas Gerais, Brazil) and collected after natural drying.

The *Pinus oocarpa* wood was obtained by cutting 100 cm logs with an average diameter of 35 cm from 25-year-old trees experimentally planted on the campus of the Federal University of Lavras (UFLA).

These two materials, the bean residues and *Pinus oocarpa* wood, were processed at the Wood Panel Experimental Unit (UEPAM) using a high-speed hammer mill and sieved for the production of agglomerated panels. The selected particles were those passing through the 40 mesh sieve and retained on the 60 mesh sieve

The resulting particles were then characterized "*in natura*" in apparent density - NBR 14810-2 (ABNT 2018), total extractives - ABNT NBR 14853 (ABNT 2010), acid-insoluble lignin - ABNT NBR 7989 (ABNT 2010) and ash content - ABNT NBR 13999 (ABNT 2017). Also, the holocellulose (H) content was calculated by difference. All tests were done in triplicate.

Specimen preparation

After the characterization, agglomerated panels were produced following five treatments (Table 1).

Table 1: Treatments to be analyzed in this study.

Treatments	<i>Pinus oocarpa</i>	Bean waste
	(%)	(%)
T1	100	0
T2	75	25
T3	50	50
T4	25	75
T5	0	100

For the production, the particles were dried to 3 % humidity in an oven and urea-formaldehyde adhesive (solids content of 70,04 %, pH 6,86, viscosity 1810 cP and gelatinization time of 53 s) was then sprayed in 12 % proportion to the dry mass through a colander until complete homogenization of the components. The mixture was then taken to a mat-forming box.

The formed mat was pre-pressed in a 30 tons capacity hydraulic press, at room temperature and at 0,4 MPa pressure. Then, metal delimiters with a thickness of 15 mm were added and the mixture was hot-pressed at 160 °C and 4,0 MPa pressure for 10 minutes (ABNT NBR 14810-2 (ABNT 2018)).

Two panels of each treatment were produced with a 0,60 g/cm³ nominal density, shaped into 250 mm x 250 mm x 15 mm (width, length, and thickness) dimensions and trimmed to normative sizes using a circular saw. The resulting samples were kept in a climate-controlled environment (20 °C ± 2 °C and 65 % ± 5 % RH) until the physical and mechanical tests were performed (ABNT NBR 14810-2 (ABNT 2018)).

Physical tests

After being produced, the specimens underwent physical water absorption (WA) tests after 24 h of immersion, according to Equation 1 (ABNT NBR 14810-2 (ABNT 2018)).

$$WA = 100 * \frac{M_w - M_d}{M_d} \quad (1)$$

Where M_w is the mass of the sample after submission and M_d is the dry mass of the sample.

The swelling in thickness (TS) after 24 h submersion was also performed, according to Equation 2 (ABNT NBR 14810-2 (ABNT 2018)).

$$TS = 100 * \frac{T_w - T_d}{T_d} \quad (2)$$

Where T_d is the thickness of the dry sample and T_w is the thickness of the sample after submersion.

The apparent density (ρ_d) of the samples was also performed by the simple division between mass and volume of samples (ABNT NBR 14810-2 (ABNT 2018)). From the density values, it was also possible to obtain the compaction rate of the panels (CR) (Equation 3).

$$CR = \frac{\rho_d}{\rho_b * (pb\%) + \rho_p * (pp\%)} \quad (3)$$

Where ρ_d is the apparent density of the particle board (g/cm^3); ρ_b is the apparent density of bean residues (g/cm^3); $pb\%$ is the bean residue content; ρ_p is the apparent density of pine wood (g/cm^3); and $pp\%$ is the pine wood content.

Mechanical tests

Mechanical tests were also performed: static bending at three points, in order to obtain the values of modulus of elasticity (MOE) (Equation 4) and modulus of rupture (MOR) (Equation 5), and perpendicular traction in order to obtain internal bond (IB) by the simple division between rupture load in traction and area of the sample. These tests were carried out at a speed of 10 mm/min in a universal testing machine “Time Group” with a load capacity of 2

tons, equipped with a computerized system for data acquisition and variable control. (ABNT NBR 14810-2 (ABNT 2018)).

$$\text{MOE} = \frac{D^3 * L}{4 * d * b * h^3} \quad (4)$$

$$\text{MOR} = \frac{3 * Lb * D}{2 * b * h^2} \quad (5)$$

Where D is the distance between machine supports; L is the load variation before the proportionality limit in the generated "Force x displacement" graphs from static bending; d is the displacement variation corresponding to the force variation; Lb is the breaking load and b and h are the dimensions of the specimen cross section.

Statistical analysis

The experimental design used in the research was completely randomized with 5 treatments and 3 replications. A linear regression analysis was performed, for the properties that showed a significant effect with different levels of bean residues, in order to verify the relationship between the increase in by-products and the values variation of the evaluated properties of the panels. A Tukey statistical analysis at 5 % probability was also performed to analyze the relationship between the “*in natura*” properties of the residue and the reference wood.

A graphical abstract of the adopted experimental procedure can be found in Figure 1.

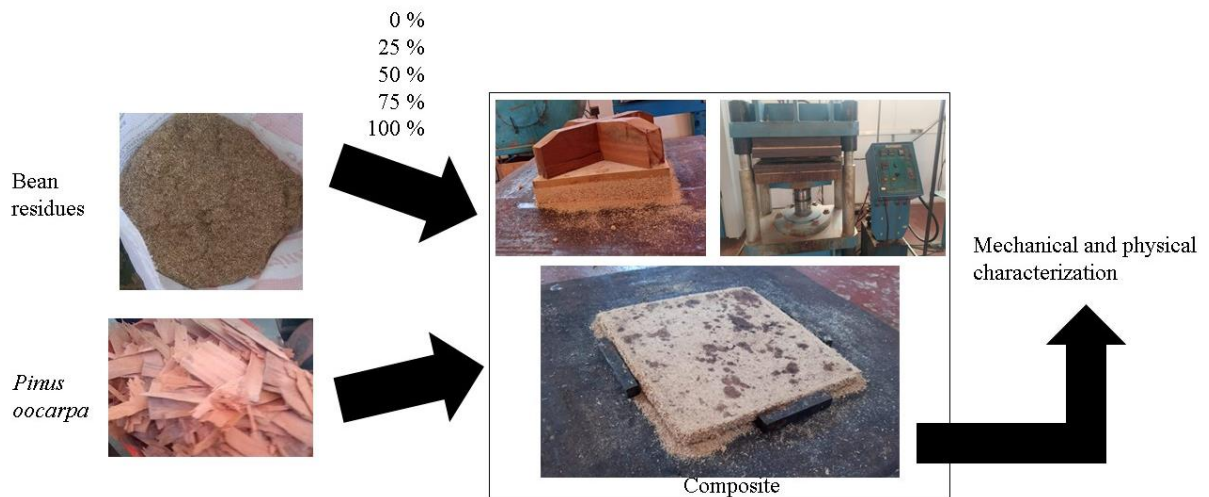


Figure 1: Graphical abstract of the adopted experimental procedure.

RESULTS AND DISCUSSIONS

Results from experiments

Table 2 shows the results obtained for the properties of “*in natura*” materials used in the research. First, it is observed that the characterization of *Pinus oocarpa* wood was similar to that found in relation to all parameters studied (Mendes *et al.* 2018, Narciso *et al.* 2020).

Table 2: Properties of lignocellulosic materials.

Material	Apparent density	Extractives	Lignin	Ashes	Holocellulose
	(g/cm ³)	(%)	(%)	(%)	(%)
<i>Pinus oocarpa</i>	0,48* (0,05) a	6,18 (0,72) a	29,28 (0,14) a	1,25 (0,03) b	63,29 (0,81) a
Bean waste	0,24 (0,02**) b	8,16 (1,60) a	8,13 (0,79) b	16,94 (0,43) a	56,55 (3,97) b

*Standard deviation of means.

**Means followed by the same letter in the line do not differ at 5 % probability by the Tukey test.

However, the density of the materials was low ($< 0,50 \text{ g/cm}^3$) according to the classification of the Technological Research Institute (IPT, 1985), and statistically different from each other. The residue presented a lower density compared to the wood as a reference and to other industrial by-products, such as vine, which had a density of $0,62 \text{ g/cm}^3$, according to Wong *et al.* (2020), but also higher than other residues such as the sugarcane bagasse, which exhibited an average data of $0,12 \text{ g/cm}^3$ for this physical property (Soares *et al.* 2017). Bufalino *et al.* (2012) exhibited that, a low density is important regarding to the adaptation of lignocellulosic materials for the panels production, thus aiming to increase particles in the same volume of panels. However, this low property can influence negatively, for example, the panels thickness swelling and, therefore, other aspects such as the chemical composition of the raw materials must also be analyzed for correct pre-analysis of the theoretical influence of residues on plastic wood panels (Iwakiri and Trianoski 2020, Guimarães Júnior *et al.* 2016).

From this perspective, with regard to extractives, hydrophobic compounds of low molecular weight which are related to decreased permeability, hygroscopicity, pressing problems and adhesion reaction in the panels, the data obtained were statistically equal from the two constituents used as raw materials for particleboard and are within the recommended range of variation of 4 % -10 % of these components due to the different factors that lead to obtaining lignocellulosic materials. Thus, even with higher values than the wood, it is expected that bean residues do not cause negative impacts on the panels on this matter (Iwakiri and Trianoski 2020, Klock and Andrade 2013). Also, according to literature the extractives content of bean residues was lower than that of other species such as coffee, which had an average content of these chemical elements of 26,24 % (Scatolino *et al.* 2017), but higher than other by-products like coconut, whit 3,15 % of extractives according to Narciso *et al.* (2020).

Lignin, responsible for providing hydrophobicity, improving the aggregation quality, and, consequently, increasing the physical-mechanical properties of the panels, presented statistically different values between both materials. The lignin content found in the agricultural by-product was 8,13 %, lower than the wood, which had 29,28 % of lignin, and also lower than other residues already used as wood replacements in particulate panels, such as hazelnut, which had 35,10 % of lignin, according to Çöpür *et al.* (2007). Therefore, it is expected that the physical-mechanical properties will be negatively impacted, regarding the presence of lignin, by the addition of bean residues in the panels (Neutelings 2011).

On the other hand, ash content can affect the adhesion process and workability of panels; however, it does not significantly alter the fundamental characteristics of the panels. The values found in this research for this component were 16,94 % for bean residues and 1,25 % for the wood. The significantly higher content of ash in agricultural by-products is common in other studies and is mainly due to differences in production and harvesting processes, such as planting location and different management conditions (Iwakiri and Trianoski 2020).

As for holocellulose, it was observed a significant reduction of this component in bean residues compared to *Pinus oocarpa* wood and also to other agricultural by-products, such as coconut, which obtained 68,75 % of this chemical in the research by Narciso *et al.* (2020). However, there was an increase in this content in relation to other residues, such as banana, which has 51,90 % of holocellulose in its chemical composition, according to Guimarães *et al.* (2014). According to Iwakiri and Trianoski (2020), normally, the use of lignocellulosic residues is limited in wood panels, since such materials have high levels of holocellulose which can affect the physical-mechanical properties of the panels due to their hygroscopicity, referring to free hydroxyl groups that can adhere to water. The trend found in the research was inverse, with the by-product presenting lower values of holocellulose than the wood, which may indicate a

possible improvement of the panel's properties containing bean residues, in relation to the content of this component.

Results from bean panels

Figure 2 shows the physical characteristics of apparent density and compaction ratio found for agglomerated panels with different additions of bean residues.

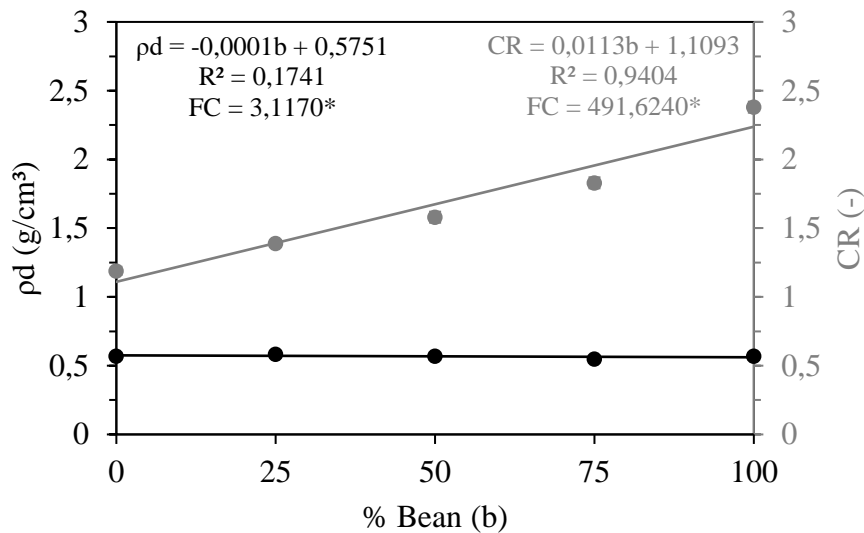


Figure 2: Density and compaction ratio of particulate panels.

* Significant regression analysis at 5 % significance.

It is observed that the apparent density was below the proposed nominal density of $0,60 \text{ g/cm}^3$ due to laboratory conditions in relation to the industrial process (Martins *et al.* 2018); however, all panels, according to CS 236-66 (CS, 1968) and ANSI A208.1-99 (ANSI, 1999) standards were classified as low density ($< 0,60 \text{ g/cm}^3$ and $< 0,64 \text{ g/cm}^3$, respectively) and, in general, were not statistically different from each other, according to the analysis of variance test ($\alpha = 0,05$). This small range of data also resulted in a low value for the linear regression coefficient (0,1741). However, it is observed that the density of the panel presented

small decreases as more bean particles are added, an expected fact, since the density of the bean is lower than the reference wood (Table 2). This fact can provide gains in the logistical process (Iwakiri and Trianoski 2020).

Regarding the compaction ratio, on the other hand, the addition of bean residues resulted in an increase of this property, proportional to the increase in the presence of these by-products in the panels. This trend was also described in other studies and also can be explained by the fact that the density values of agricultural residues are significantly lower compared to the wood (Scatolino *et al.* 2017, Guimarães Júnior *et al.* 2016).

Maloney (1993) recommended values between 1,3-1,6 for this property. Replacing these values in the regression generated in Figure 2, it is observed that the values for meeting such reference are between 16,8 % and 43,2 % of bean insertion in the agglomerated panels. However, the author stipulated such values for particleboard panels produced with wood and not lignocellulosic waste, and, therefore, this range may be different for panels similar to those described in this project.

On the other hand, the properties of water absorption and thickness swelling (Figure 3) also showed a general tendency to increase due to the increase in the addition of agricultural by-products. The data obtained by the panels with the addition of waste did not show a significant difference between them and were higher than the values found for the reference panels and also for products made from the raw material of other agricultural residues, such as hazelnut (Çöpür *et al.* 2007), rice (Ayrilmis *et al.* 2012) and cotton (Nguyen *et al.* 2020).

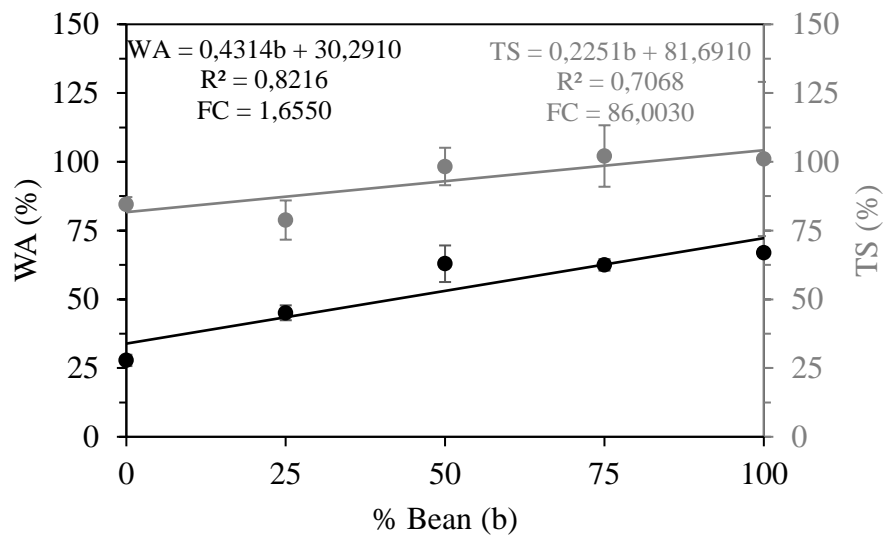


Figure 3: Water absorption and thickness swelling of particulate panels.

* Significant regression analysis at 5 % significance.

This upward trend is explained in the literature essentially by the large presence of holocellulose in the waste, these structures are highly reactive with water, by the low presence of lignin, hydrophobic structure, and also by the high compaction ratio of the panels (Figure 2) (Iwakiri and Trianoski 2020). Regarding normative limits, no panel met CS 236-66 (CS, 1968) standard of TS property (maximum 35 %).

The modulus of elasticity (MOE) and modulus of rupture (MOR) values, derived from the static bending, are shown in Figure 4. Worth noting that both properties were significantly affected by the addition of bean residues. The values varied between 1,43 MPa - 6,55 MPa for the MOR and 190,87 MPa - 741,29 MPa for the MOE and were lower than those found in panels with the addition of other agricultural residues, like corn (Prasetyo *et al.* 2020). This reduction in the mechanical properties of stiffness and strength in the panels containing residues, may be associated with the low values of lignin found in the particles of this agricultural element (Iwakiri and Trianoski 2020, Neutelings 2011).

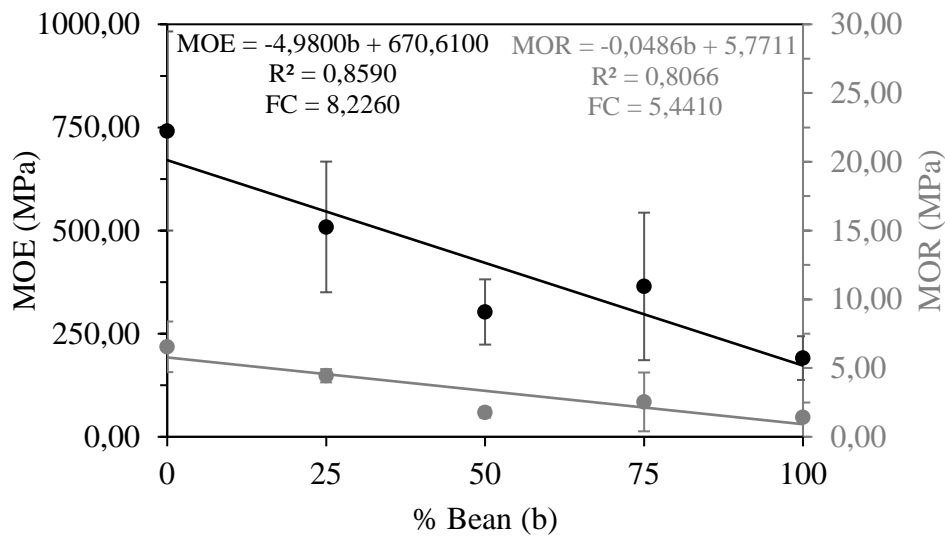


Figure 4: Values obtained for MOE and MOR of the particulate panels.

* Significant regression analysis at 5 % significance.

IB values (Figure 5), on the other hand, ranged between 0,06 MPa - 0,25 MPa. Such values were lower than in other similar literature that used, such as vine residues (Wong *et al.* 2020), cotton (Nguyen *et al.* 2020), or corn (Prasetiyo *et al.* 2020) in wood panels. This trend may indicate that the adhesive used affected IB and several other properties of the panels. It is also argued that all panels with the addition of residues obtained significantly lower IB values than the reference sample, which may also be related to the low values of lignin found in the particles of the agricultural by-product (Iwakiri and Trianoski 2020, Neutelings 2011).

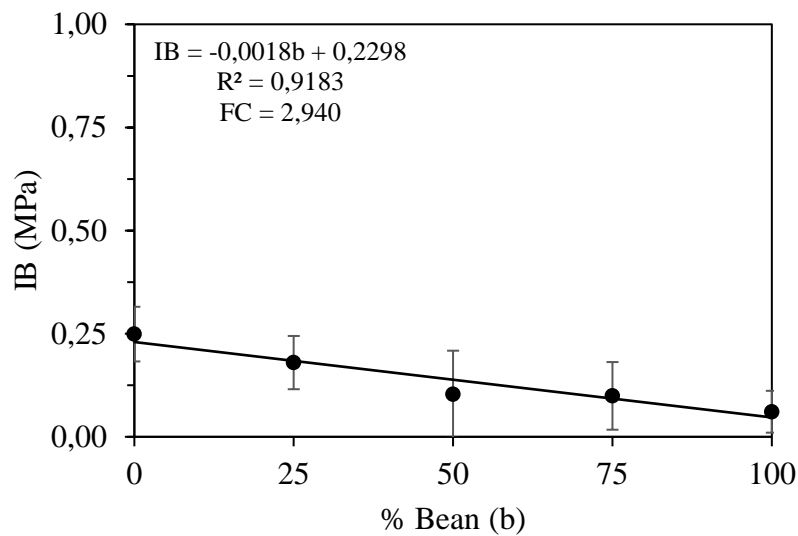


Figure 5: IB properties of particulate panels.

* Significant regression analysis at 5 % significance.

Regarding normative documents, ANSI A208.1-99 (ANSI, 1999) recommends that low-density particleboards must present minimum values for MOE, MOR, and IB of 550 MPa, 3 MPa and 0,14 MPa respectively. By replacing these values in the linear regressions generated in Figures 4 and 5, it is observed that the maximum value of bean residues to be added to the panel to comply with the standard is 24,22 % for the MOE, 57,02 % for the MOR, and 49,88 % for IB.

CONCLUSION

According to the results of the characterization of the particles "*in natura*", from bean residues, compared to *Pinus oocarpa* wood, density values were lower and the lignin, holocellulose, and the extractives content presented higher values.

Regarding the characterization of the panels, there was a uniformity trend towards the apparent density that met the proposed standards. Furthermore, there was an increase in the compaction ratio, water absorption, and thickness swelling properties; besides a reduction in the mechanical properties concomitant with the increase in the addition of the by-product in the composites.

In this way, the research presented important results aiming at the propagation of this sustainable process, mainly in the furniture industries, aiming to reduce the high demand of native trees for commonly underused residues.

However, more studies are needed to gain a better understanding of the effects of adding bean residues to particle boards. In these new studies, pretreatments could be used on the particles to reduce their affinity for water.

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AUTHORSHIP CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Eduardo Hélio de Novais Miranda and Diogo Antonio Correa Gomes. The first draft of the manuscript was written by Eduardo Hélio de Novais Miranda and Diogo Antonio Correa Gomes and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**ARTIGO 2 - AVALIAÇÃO DA INFLUÊNCIA DA ADIÇÃO DE RESÍDUOS DE
FEIJÃO EM MATRIZES DE GESSO**

Artigo 2 - Redigido conforme norma do periódico científico - Versão publicada	
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**EVALUATION OF THE INFLUENCE OF THE ADDITION OF BEAN RESIDUE IN
GYPSUM MATRICES**

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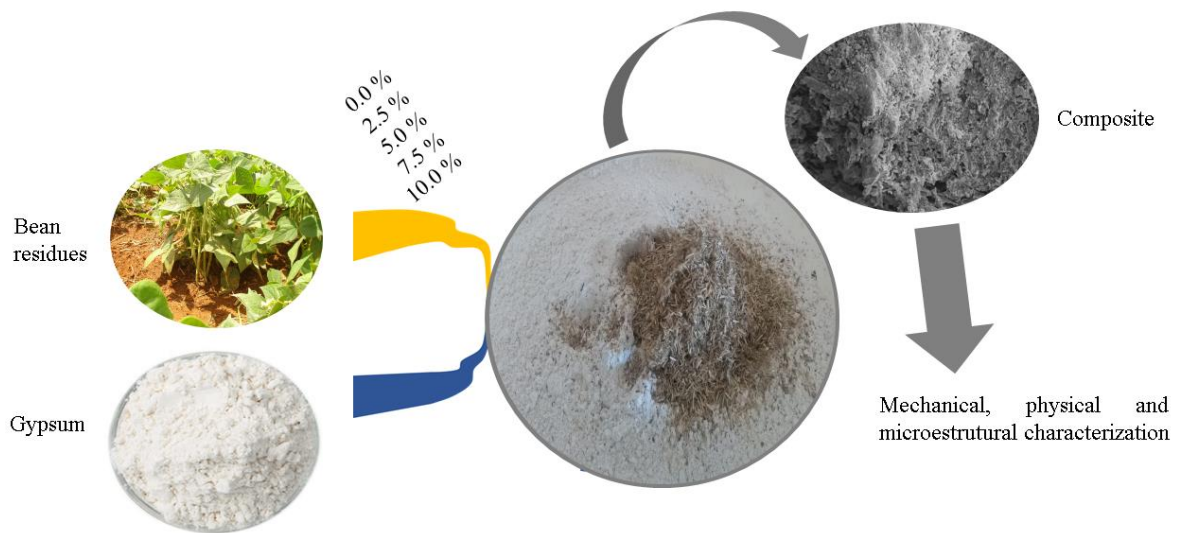
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ABSTRACT

In order to reduce the production of cement, several alternatives have been studied. Among them, gypsum presents itself as a viable option, since it is already used in internal finishing; however, this material can still be improved. The objective was to improve the physical and mechanical efficiency of gypsum by developing a material with the incorporation of natural fibers from bean residues. For this, the lignocellulosic material was first characterized *in natura*. Subsequently, different contents of bean fiber residues (0.0 %, 2.5 %, 5.0 %, 7.5 % and 10.0 %) were added in replacement to gypsum in matrices with a constant 0.6 gypsum:water ratio. In order to evaluate the influence of the addition of bean residue in the gypsum matrix, mechanical tests of bending and compression and physical tests of moisture on dry basis, apparent density, water absorption, thermal conductivity and acoustic insulation were carried out. Scanning electron microscopy (SEM) images were also taken. In general, satisfactory results were obtained with the incorporation of bean fiber residues; as an example, the physical characteristics of the composite with 10.0 % incorporation can be cited, which demonstrated a decrease in apparent density, improvement in acoustic insulation and stability of thermal conductivity. As for the mechanical characteristics, the incorporation of 5.0 % of bean residue stood out, obtaining the best results in the bending tests. Therefore, given the initial positive results, further studies are needed in order to confirm the prospect of this composite as a viable option for application in civil construction.

Keywords: Natural fibers · Residue · Low environmental impact products · Composites.

GRAPHICAL ABSTRACT



INTRODUCTION

Cement is the second most consumed material in the world. It has been used by mankind in the construction of their residences for centuries and due to the incessant search to adapt it to the new needs of civil construction, it has gone through remarkable evolution. In fact, cement has several qualities, however, in order to make its production possible, the environment suffers severe damage, such as the degradation and contamination of water and soil and the release of atmospheric gases that increase the greenhouse effect and can cause respiratory problems to the local population (Maury and Blumenschein 2012).

In order to reduce the production and consumption of cement, different forms of substitution for other materials have been studied. According to Vimmrová et al. (2011), gypsum plaster is a great alternative to cement, since it is already widely used in internal finishing in civil construction and which, when compared to conventional binders, has the advantages of the easy preparation method, high cost benefit, great ability to mold itself into different shapes, good thermal insulation and ability to regulate humidity inside homes. On the

other hand, gypsum plaster has low tensile and flexural strength (Kuqo and Mai 2021). These disadvantages may be limiting factors in the use of gypsum, since in some of its applications superior mechanical and physical properties to those presented by the material are required.

According to Bijen and van der Plas (1992), the incorporation of fibers as reinforcement in plaster can be an alternative to improve its mechanical properties. Fiber-reinforced materials also have improved energy dissipation, stiffness, ductility, and impact resistance.

Taking that into consideration, a wide variety of reinforcements have been tested, such as the following synthetic and natural fibers: glass fibers (Martias et al. 2014), textile fibers, polyamide fibers, polypropylene fibers (Gencel et al. 2014; Medina and Barbero-Barrera 2017), microfibers from shredded tires (Parres et al. 2009), among others. However, synthetic fibers are increasingly losing ground to natural fibers due to their non-renewable and non-biodegradable nature (Li and Li 2014; Lushnikova and Dvorkin 2015).

Natural fibers present, in this context, renewable nature, biodegradability, low density, low cost, good combination of mechanical and physical-thermal properties and good interaction with matrix phases, factors that qualify them to possibly improve the characteristics of gypsum matrices that contain them. In the literature, research has already been done about the interaction of natural fibers with plaster matrices and their proportions in relation to physical characteristics (Dalmay et al. 2010; di Bella et al. 2014). Different natural fibers have been used for that, such as sisal, cotton stalk, wood, date palm (Djoudi et al. 2014), palm kernel fruit, kenaf, coconut (Tilak et al. 2015), among others.

Another type of natural fiber, still not often used in civil construction, are the fibers from bean residue. With a great abundance and potential to add to the physical characteristics of gypsum, they present themselves as a possible improvement for this product. According to CONAB (2021), the planting of beans in Brazil is carried out on a large scale, with the harvest of 2020/2021, for example, reaching the production of approximately 2.86 million tons of

beans. It is estimated that the production of residues, such as pods, branches, stems, leaves, roots, etc. from this crop is about 1.43 million tons. Part of this waste is underused or even disposed of incorrectly in nature.

The objective of this study is, in this context, to evaluate the interaction between bean residue fibers and plaster matrices through the analysis of the physical-mechanical properties of plaster with the incorporation of different fiber content of bean residue (0.00 %, 2.50 %, 5.00 %, 7.50 % and 10.00 %).

MATERIALS AND METHODS

Materials

In order to carry out the research, bean fiber residue (*Phaseolus vulgaris*) (stem and pod) was collected from Pimentas farm, located in the municipality of Lavras (latitude 21°15'58.5" S and longitude 45°03' 31.5" W). The plaster used in the molding was purchased locally in Lavras, with specifications in accordance with EN 14496 (CEN 2017).

Residue processing

The bean residue was sent to the Experimental Unit for Wood Panels (UEPAM) at the Federal University of Lavras (UFLA), processed in a high-speed hammer mill and sieved. The selected particles were those passing through the 40 mesh sieve and retained on the 60 mesh sieve.

Residue characterization

The particles formed were characterized *in natura* through the tests shown in Table 1. The content of holocellulose (H) was also calculated by percentage difference in relation to the other chemical components (extractives, lignin and ash).

Table 1 Residue characterization

Test	Standard
Apparent density	NBR 14810-2 (ABNT 2018)
Soluble materials in ethanol-toluene and in dichloromethane and in acetone (extractives)	NBR 14853 (ABNT 2010)
Acid-insoluble lignin	NBR 7989 (ABNT 2010)
Ash content	NBR 13999 (ABNT 2017)

The scanning electron microscopy (SEM) technique was also performed using a SEM Zeiss EVO 40 device (Oberkochen, Baden-Württemberg, Germany) to evaluate the surface of the residue. For this, the fibers were gold-coated and secondary electrons and backscatter detectors were used. The microscope was operated under accelerating voltage of 15 kV, probe current of 2 nA at a working distance of 10 mm, without tilting and different image magnifications.

Finally, the energy dispersion x-ray spectroscopy (EDS) technique was used to characterize the chemical elements of the residue. The samples were carbon-coated in order to generate the electrical conductivity necessary for the analysis and the microscope utilized the same parameters of the SEM analysis.

Production of the composite

The composites were molded from the raw materials described above through 5 treatments as recommended by Oliveira et al. (2020):

- T1 - 100.00 % plaster and 0.00 % bean residue;
- T2 - 97.50 % plaster and 2.50 % bean residue;

- T3 - 95.00 % plaster and 5.00 % bean residue;
- T4 - 92.50 % plaster and 7.50 % bean residue;
- T5 - 90.00 % plaster and 10.00 % bean residue.

The dimensions of the specimens were 40.00 x 40.00 x 160.00 mm, according to the EN 13279-2 (CEN 2014). Six specimens were molded per treatment, with a water/plaster ratio of 0.6, as recommended by Oliveira et al. (2020).

During the period of 24 hours, the specimens solidified, allowing their demolding and storage in a well-ventilated place, free from the action of weather. Tests were performed after the seventh day of curing.

Characterization of composites

After the production of the specimens, the tests shown in Table 2 were carried out in order to evaluate the influence of the bean residue on the properties of the composites.

Table 2 Tests performed on the composites

Test	Standard
Bending and compression strength	EN 13279-2 (CEN 2014)
Moisture on dry basis (W)	NBR 7190 (ABNT 1997)
Apparent density (ρ)	NBR NM 45 (ABNT 2006)
Water Absorption (AA)	ASTM D570-98 (ASTM 2018)
Thermal conductivity (K)	JIS 1412-2 (JSA 2016)
Sound insulation	ISO 10534-2 (ISO1998)

An analysis was also performed on the residual composite material from the bending tests, using the SEM technique, to verify the type of fracture that occurred and the interaction

between the bean residue particles and the gypsum. The parameters were the same as those adopted for the residue.

Experimental design

In order to verify the effects of treatments on the quality of the panels, a completely randomized design was used. The data from the analyzed properties were submitted to linear regression, analysis of variance (ANOVA) and also to the Tukey test at 5.00 % probability, to compare the means.

RESULTS AND DISCUSSION

Characterization of lignocellulosic material

In Table 3, the average values of apparent density and content of extractives, lignin, ash and holocellulose of the bean residue can be observed.

Table 3 Chemical characterization of bean residue

Material	Apparent density (g/cm ³)	Extractives (%)	Lignin (%)	Ashes (%)	Holocellulose (%)
Bean Residue	0.24 ^{(0.02)*}	8.16 ^(1.60)	8.13 ^(0.79)	16.94 ^(0.43)	56.55 ^(3.97)

*Standard deviation of means

The apparent density of bean residue analyzed was 0.24 g/cm³, similar to that found for cocoa residue (0.22 g/cm³) (Veloso et al. 2021), soybean pods (0.20 g/cm³) (Lisboa et al. 2020) and sugarcane bagasse (0.121 g/cm³) (Soares et al. 2017). The low density found in biomass residues compared to gypsum (0.80 g/cm³) makes them attractive for making the composite lighter (EN 13279-1 (CEN 2008)).

The chemical compositions and structure of the biomass are highly variable and are influenced by origin, climatic conditions, age and location in the plant (Jawaid et al. 2017). The extractive content found was 8.16 %, a low value compared to that found by Paula et al. (2011), who analyzed stem and pod residues separately and obtained values of 7.55 % for stem residues and 18.19 % for pod residues; Brum et al (2006) considered the residues together and found an extractive content of 22.70 %. Paula et al. (2011) also analyzed other plant biomass residues from rice, sugarcane, wood, corn and soybeans, finding extractive contents between 4.06 % (rice husk) and 31.76 % (sugarcane bagasse). For soybeans, for example, values of 6.87 % were obtained for stem residues and 21.77 % for pod residues. A lower content of extractives is an important characteristic, as the presence of higher amounts of minerals and some non-polar extractives can result in the blocking of reactive chemical groups, which can compromise the mechanical performance of the composite (Mesquita Júnior et al. 2018).

Lignin content found in the residue was 8.13 %, close to that found by Brum et al. (2006) (8.40 %) and lower than that found by Paula et al. (2011) (21.61 % for the stem and 11.99 % for the pod). For other residues, Paula et al. (2011) obtained lignin contents between 9.29 % (corn straw) and 26.90 % (rice husk). Soybean residues presented contents of 21.64 % for the stem and 17.16 % for the pod. Higher contents of extractives and lignin can lead to higher setting times, as these components act as retarders of gypsum hydration kinetics (Shiroma et al. 2016). Furthermore, lignin is responsible for a weaker interaction with the matrix, negatively influencing the mechanical behavior of the composite (da Fonseca et al. 2021).

The amount of ash (16.94 %), on the other hand, was higher than that of Paula et al. (2011) (between 4.61 and 6.65 %) and Brum et al. (2006) (4.30 %). A significant ash content in agricultural by-products is commonly found in other researches and is mainly due to differences in production and harvesting processes, such as planting location (Iwakiri and

Trianoski 2020). For example, Ahmad et al. (2021) and Sun et al. (2021) found ash contents of 20.90 % and 15.70 %, respectively, in soybean residues.

Finally, the residue characterized in this study had a holocellulose content of 56.55 %, close to that of Paula et al. (2011) (63.17 to 66.23 %), while Brum et al. (2006) found a content of 71.70 %. Other biomass residues in the study by Paula et al. (2011) presented cellulose contents between 52.61 % (rice husk) and 83.28 % (corn straw). Due to the hydrophilic nature of cellulose, which is related to the presence of hydroxyl groups in its structure, higher contents of this component result in greater water absorption by the composite. Moisture absorption involves poor dimensional stability (swelling of the fibers), which in turn leads to the presence of microcracks inside the composite, resulting in worse mechanical properties (Iucolano et al. 2018).

Table 4, however, shows the presence of several elements in the bean residue, results obtained using the EDS technique.

Table 4 EDS of bean residues

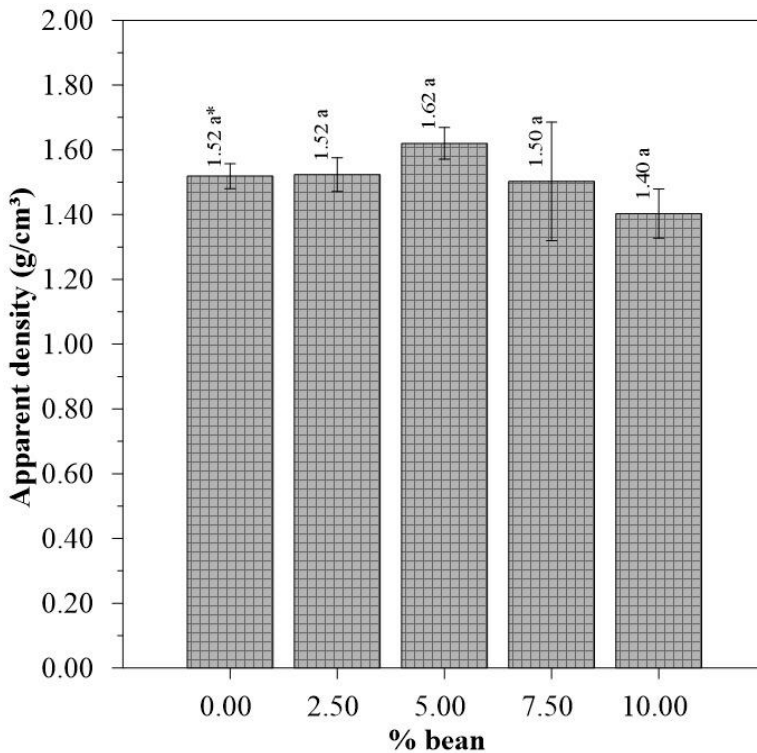
Element	O	F	Ca	Al	Mg	Fe	Si	K	S
Mass (%)	15.19	1.58	1.26	1.20	0.45	0.27	0.25	0.23	0.15
Atoms (%)	82.37	7.24	2.73	3.89	1.60	0.42	0.79	0.52	0.42

Due to the fact that the samples were bathed in carbon, this element was not detected by this analysis. Oxygen is a component of holocellulose and lignin present in the material. The other elements are likely related to the presence of extractives and ash in the lignocellulosic residue. Furthermore, by their very nature, residues are leftovers from other processes and, therefore, can be contaminated or improperly stored (Paula et al. 2011).

Physical characterization of composites

Apparent density

The results of the plaster composites density test are shown in Fig. 1.



*Means followed by the same letter in the line do not differ at 5.00 % probability by the Tukey test

Fig. 1 Apparent density results found in samples with different proportions of gypsum replacement by bean residues

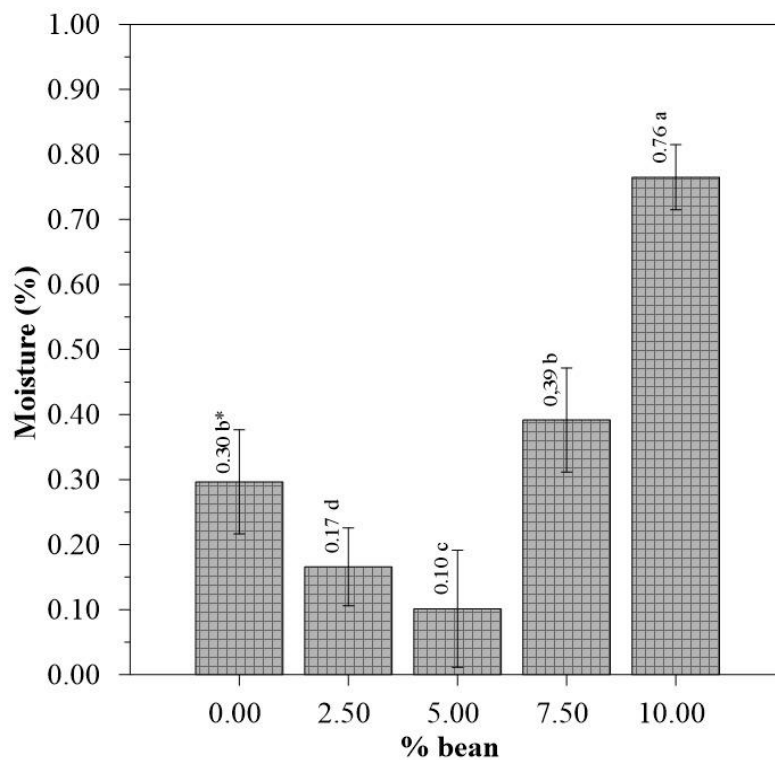
The density of the material was stable across all treatments, with minimal variations. Comparing the values found, it is observed that the five treatments were statistically equal, according to Tukey's Test ($\alpha = 0.05$).

In general, the apparent density of the material decreased, ranging from 1.62 g/cm³ to 1.40 g/cm³. This occurs because the specific mass of plaster is greater than that of bean fiber residues (Table 3). The decrease in composite density in comparison to the matrix is reported

in other studies, such as Rivero et al. (2014), who incorporated rubber into the plaster matrix, Chinta et al (2013), who made plaster composites reinforced with plant fibers and Morales-Conde et al. (2016), who incorporated demolition wood waste into plaster-based composites.

Moisture

Moisture of composites from different treatments is shown in Fig. 2.



*Means followed by the same letter in the line do not differ at 5.00 % probability by the Tukey test

Fig. 2 Moisture results found in specimens containing gypsum and bean residues

An initial decrease in moisture is observed when incorporating bean fiber residues up to 5.00 %. Beyond this level of replacement, the moisture increases with the amount of waste incorporation. According to Veloso et al. (2021), the increase in hydrophobicity with the insertion of the residue is a beneficial characteristic for plaster, since it can reduce its restriction

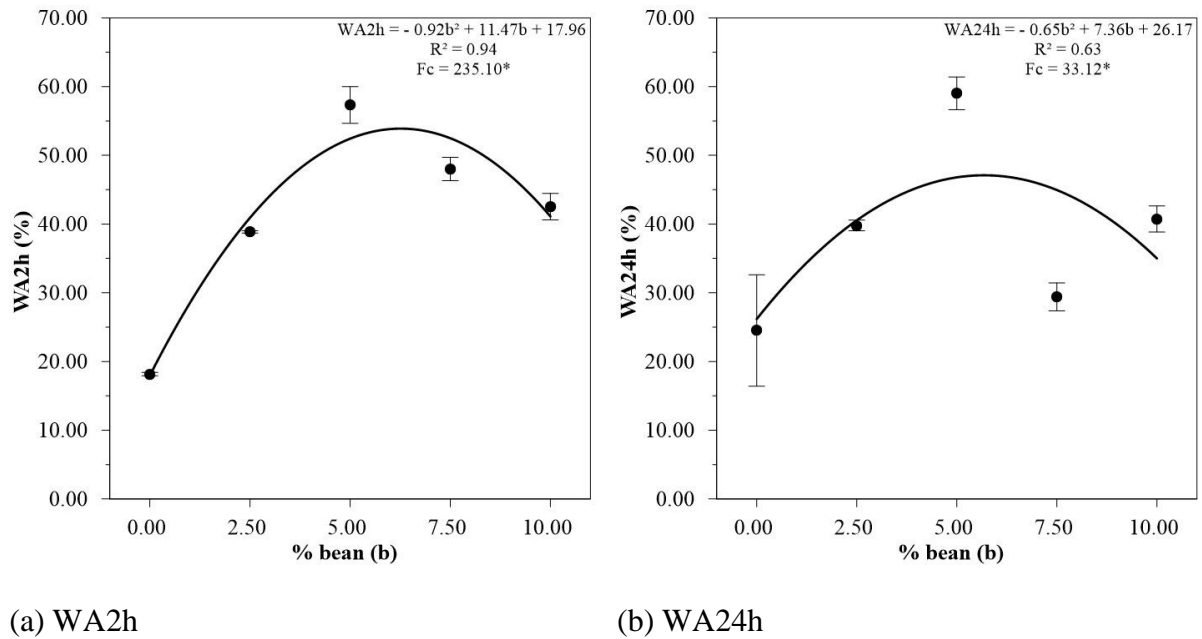
to dry environments and expand its use for composites. According to the authors, the increase in moisture occurs due to the combination of cellulose and hemicellulose (holocellulose), which, due to its hygroscopic character, causes the product to adsorb more moisture. The decrease in moisture occurs due to the lignin and extractive contents of the residue.

Humidity also presented great variations among the different treatments, finding statistically equivalent results only for 0.00 % and 7.50 %. A decrease of 66.60 % was found between the moisture of the specimen of 0.00 % and 5.00 % and an increase of 246.00 % between 0.00 % and 10.00 %. According to Chinta et al. (2013) a controlled increase presents values below 200.00 % and, therefore, the increase in humidity in the treatment of 10.00 % incorporation is considered uncontrolled, while the other results can be considered as controlled.

The maximum variations found are between 66.60 % and 246.00 %. In those composites containing 2.50 % and 5.00 % bean residues, where humidity decreased, values found were close to those found by Veloso et al. (2021), who studied plaster composites reinforced with particles of cocoa agro-industry residue. On the other hand, in composites containing 7.50 % and 10.00 % bean residue, in which an increase in humidity was observed. The results are close to those found by Chinta et al. (2013), who studied plaster composites reinforced with plant fibers and de Oliveira et al. (2020) who studied composites with plaster matrix reinforced with wood fibers.

Water absorption

Fig. 3 shows the water absorption graphs of plaster composites at 2 (WA2h) and 24 (WA24h) hours.



* Significant regression analysis at 5 % significance

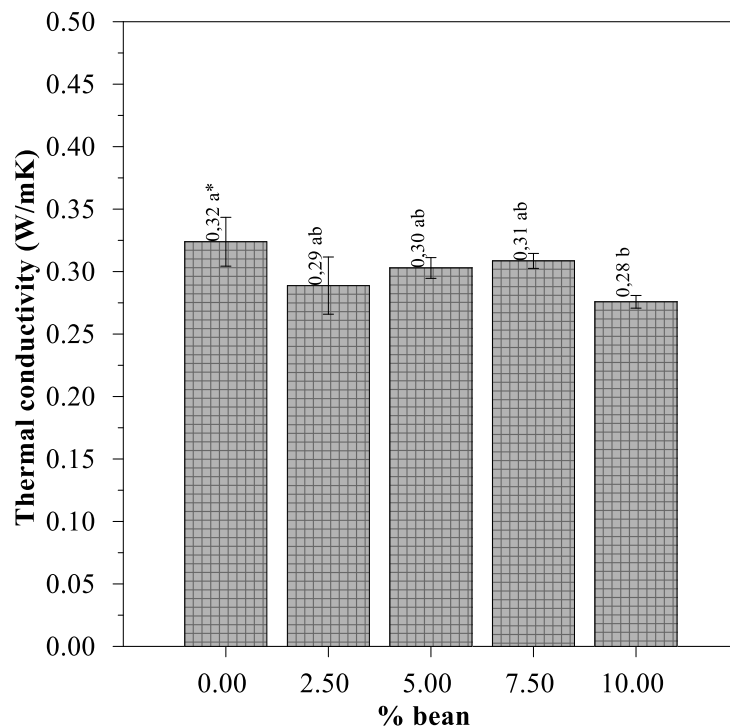
Fig. 3 Water absorption results found in specimens containing gypsum and bean residues

It is observed that when incorporating different percentages of bean fiber residue, water absorption values increased, presenting the highest value at 5.00 %, in both graphs. Veloso et al. (2021) found that water absorption decreased with the increase of lignocellulosic residue content, contrary to the results found in this research. This difference is due to the lignin content of the fiber, since lignocellulosic materials have hydrophobic characteristics, being responsible for the decrease in water absorption. The bean fiber had 8.13 % lignin (Table 3), while cocoa has 35.15 % (Veloso et al. 2021).

It is noted that most of the water absorption in the composite specimens refers to the first two hours of curing. The specimen with 0.00 % of bean fiber residues presents 74.00 % of the absorption in the first two hours, when compared to the 24-hour graph. The specimens with the incorporation of bean fiber residues showed similar behavior, presenting an average of 98.00 % of the water absorption in the first two hours.

Thermal conductivity

Fig. 4 presents the results of thermal conductivity of the plaster composites with different content of bean residues.



*Means followed by the same letter in the line do not differ at 5 % probability by the Tukey test

Fig. 4 Thermal conductivity values found in different specimens with different proportions of gypsum replacement by bean residues

These results point to a small difference between treatments. The 0.00 %, 2.50 %, 5.00 % and 7.50 % specimens are statistically equivalent. In addition, the result of the 10.00 % sample differs from the reference but is statistically equal to the other specimens.

Thermal conductivity results range from 0.28 W/mK to 0.32 W/mK. Noronha (2014) obtained similar results in the mixture of plaster with pulp from Kraft paper, with a thermal conductivity of 0.25 W/mK and in the mixture of plaster with banana fiber, with a thermal

conductivity of 0.44 W/mK. Medeiros (2017) also found similar results when incorporating different materials into a plaster matrix: leather residue, plain paper, Kraft paper and Vinyl Acetate (EVA) powder, with the respective values of 0.25 W/mK, 0.24 W/mK, 0.23 W/mK and 0.23 W/mK.

According to Villela et al. (2020), plaster has low thermal conductivity, due to the low conductivity of the air trapped in its pores, which causes the material to be resistant to the passage of heat.

Sound insulation

Fig. 5 shows the results of the acoustic insulation test. In relation to the control, the composites reduced the sound intensity in all analyzed frequencies. These results are in agreement with those observed by Veloso et al. (2021) for gypsum-based composites reinforced by lignocellulosic residues. Sound absorption in gypsum composites is related to their porosity, especially to the presence of interconnected pores (Jia et al. 2021). When a porous material such as gypsum is exposed to sound, the air molecules inside the pores of the material vibrate, transforming some energy into heat (Moretti et al. 2016). Composites containing bean residues showed reductions in sound intensity on average 0.23 dB greater compared to the reference material, across all frequencies. At the frequency of 1000 Hz, the greatest differences between treatments can be observed. At this frequency, the composite containing 10 % bean husk presented the best result, with a measured sound intensity of 46.4 dB, while for the control the measured value was 57.27 dB.

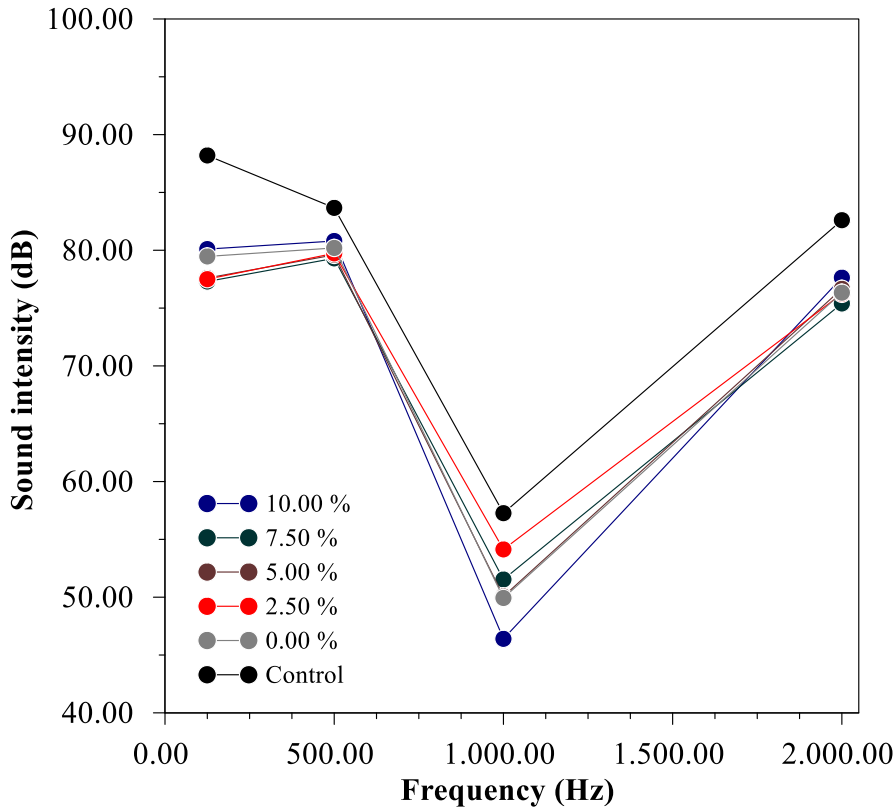


Fig. 5 Acoustic insulation of composites at different frequency levels

Mechanical characterization of the panels

In the compression test (Fig. 6), it was observed that the MOR of the material with 5 % of gypsum replacement by bean husk was superior to the others, with an average compressive strength of 16.8 MPa. The values found, with the exception of the composite containing 5 % residue, are close to those found by Oliveira et al. (2020) for gypsum composites reinforced with eucalyptus wood fibers, which were found between 7.83 and 10.36 MPa, and by Alcaraz et al. (2019), who obtained values between 9 and 11 MPa for the compressive strength of gypsum composites reinforced with jute fibers. Observation of Fig. 6b revealed that the MOE tends to decrease with higher contents of residue. The tendency to reduce mechanical properties with the use of larger amounts of reinforcement may be related to a weak interaction between reinforcement and matrix. A possible relevant factor for this weak interaction are constituents of the bean residue, such as lignin and extractives, as discussed in the characterization of the

residue (Table 3) (Veloso et al. 2021). All composites produced exceeded, however, the minimum value of 2 MPa required by EN 13279-1 (CEN 2008) for the compressive strength of gypsum.

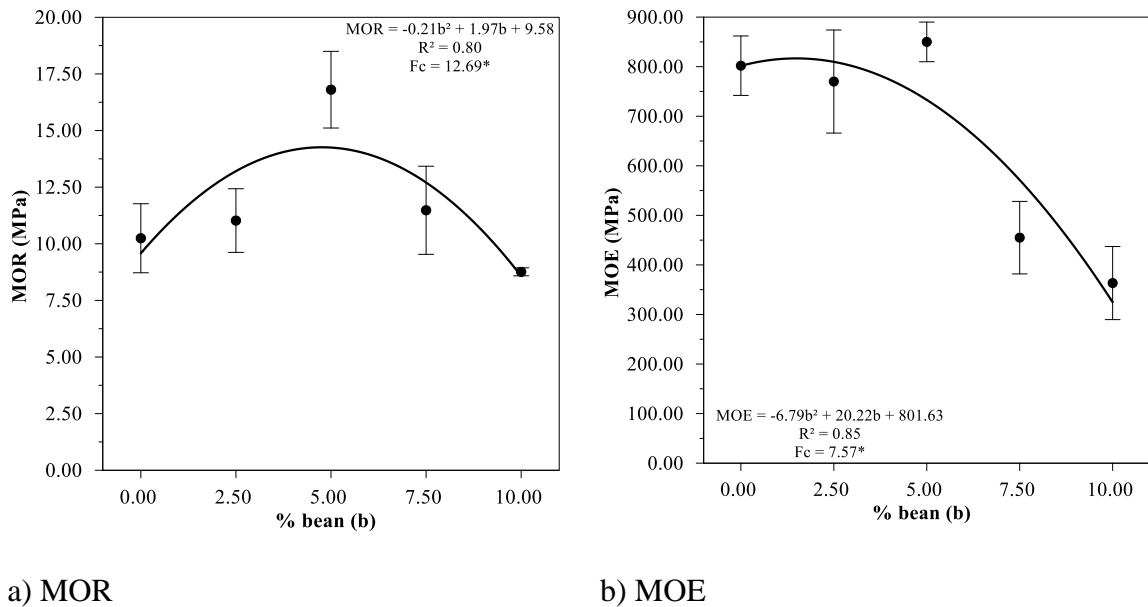


Fig. 6 Values of composite properties from the compression test

The results of the bending tests can be seen in Fig. 07. The average bending strength of the reference material was 3.64 MPa. Other authors, such as Oliveira et al. (2020) and Silva et al. (2014), found similar values of 3.38 MPa and 3.1 MPa, respectively. For MOE (modulus of elasticity) and MOR (modulus of rupture) in bending, no statistically significant differences were observed between treatments or reference material. The flexural strength values observed are between 3.23 and 5.57 MPa and were higher than those observed by Iucolano et al. (2015) in gypsum composites reinforced with abacá fibers (between 2.46 and 2, 95 MPa, fiber contents from 0 to 3%) and by Chinta et al. (2013), with reinforcements of coconut, jute, banana, cotton and wool fibers (between 0.8 and 2.9 MPa, fiber contents 0 to 3% fiber). All composites also met the requirement of EN 13279-1, (CEN 2008) of 1 MPa for flexural strength.

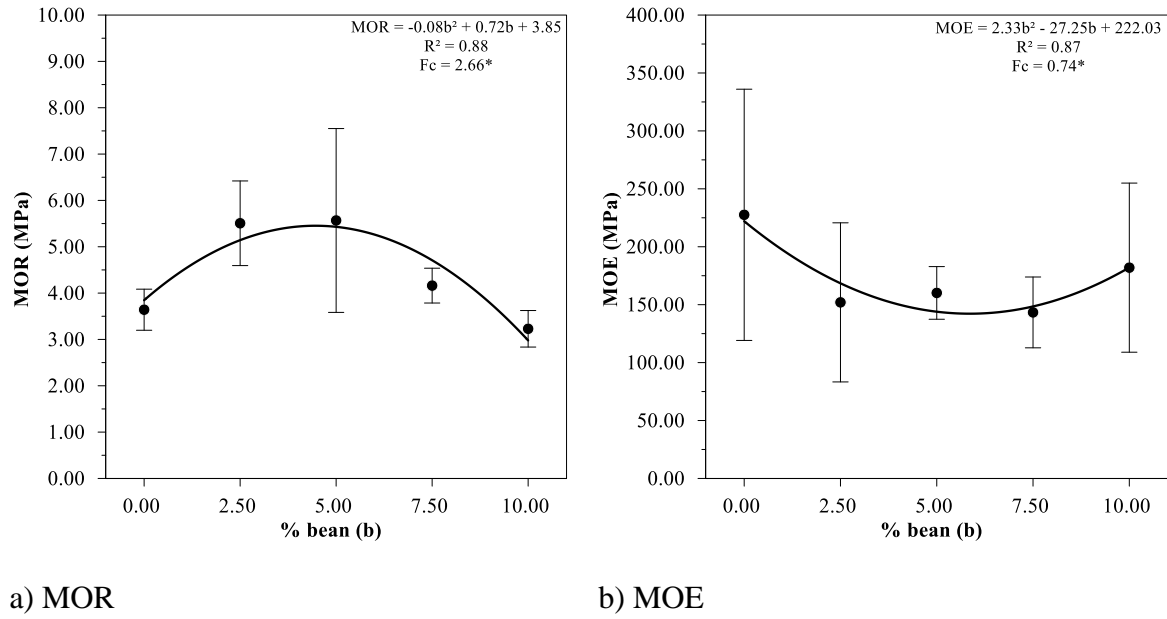
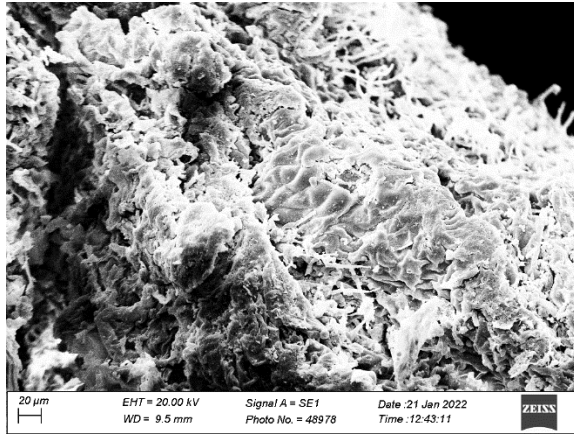


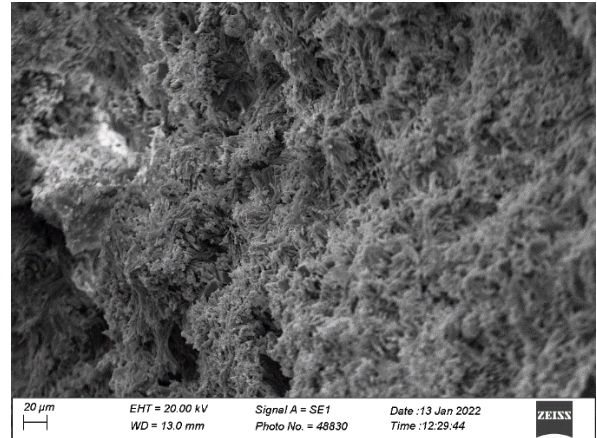
Fig. 7 Values of the properties of the samples from the static bending test

Scanning electron microscopy (SEM) analysis

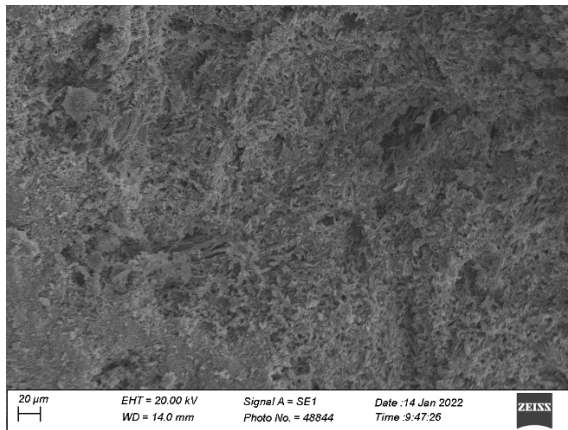
Fig. 8 shows the images, obtained by the scanning electron microscope (SEM), of the bean residue and the specimens of the bending tests, after the test, of the reference material (plaster) and the composites containing different contents of bean residues. In the images of gypsum and composites (Fig. 8b to 8f), the porous structure of the gypsum matrix can be observed, which corroborates results such as the acoustic insulation of these materials. Fig. 8e shows the presence of grooves, resulting from the detachment and pulling out of the bean fibrous residue, indicating that there is a weak interaction between the reinforcement and the matrix. In the high-stress areas of the matrix, cracks develop and reach the fiber, then grow along the matrix-fiber interface. Therefore, the failure energy dissipates along the matrix-fiber interface, leading to fiber detachment and pullout; this may be related to the decrease in mechanical strength with the use of higher levels of bean residues (Jia et al. 2021).



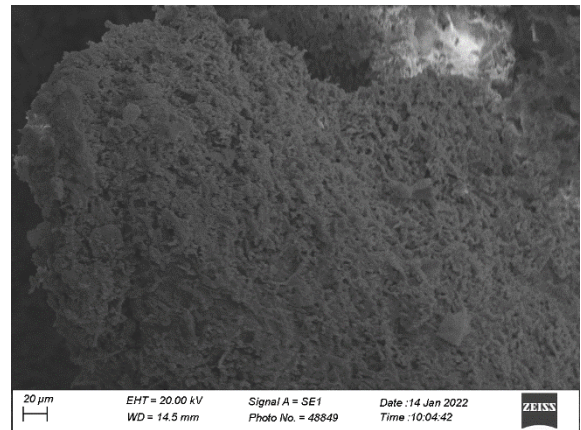
a) bean residue



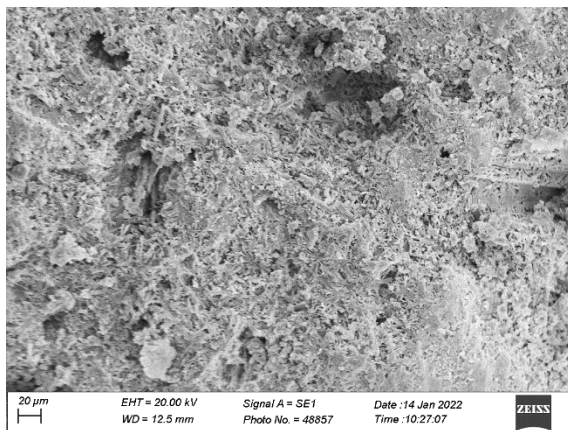
b) gypsum matrix



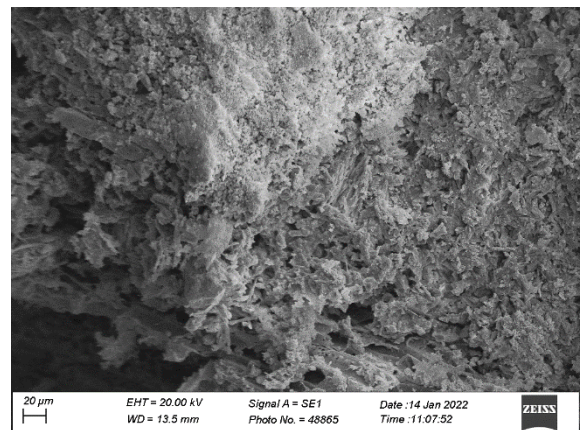
c) composite with 2.5 % bean residue



d) composite with 5 % bean residue



e) composite with 7.5 % bean residue



f) composite with 10 % bean residue

Fig. 8 SEM images of:

CONCLUSION

This study presented the physical and mechanical characterization of plaster composites reinforced with bean particles.

Humidity results ranged from a decrease of 66.60 % (between 0.00 % and 5.00 % specimens) to an increase of 246.00 % (between 0.00 % and 10.00 % specimens) in comparison to the reference material. There was an initial decrease in moisture when incorporating the bean fiber residues up to 5.00 % and, beyond this level of replacement, humidity increased rapidly with residue incorporation.

In general, the apparent density of the material was stable, with statistically equal values being obtained among the different treatments. There has been, however, a small decrease, with values ranging from 1.62 g/cm³ to 1.40 g/cm³;

Regarding water absorption, the specimens without the incorporation of bean residues absorbed 74.00 % water within the first two hours, while the specimens with the incorporation of the lignocellulosic material absorbed 98.00 % of the water within the same timeframe. There is, therefore, an increase in water absorption when incorporating this residue, with the highest value observed being with 5.00 % incorporation;

Thermal conductivity ranged from 0.28 W/mK to 0.32 W/mK. However, results were not statistically different for most specimens, indicating that the incorporation of bean residues has little effect on this property.

The composites showed good acoustic insulation. In relation to the control, all specimens reduced the sound intensity in all analyzed frequencies. Furthermore, composites containing bean residues presented reductions to sound intensity on average 0.23 dB higher compared to the reference material;

The composites also showed, mostly, an increase in mechanical properties up to 2.5% of replacement and decrease from this content;

Finally, the SEM images showed porous matrices, presence of grooves and cracks, mainly in materials with greater presence of bean residues, explaining the mechanical behavior presented.

Therefore, these preliminary results point to a trend towards the feasibility of utilizing this agricultural by-product in the production of gypsum composites.

New research is required, however, for a better understanding of the morphological, chemical and mechanical properties of these materials. The use of pre-treatments on the bean residue particles aiming at improving the main problem found in this research, the affinity of this material with water, should also be explored.

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COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Eduardo Hélio de Novais Miranda and Diogo Antonio Correa Gomes. The first draft of the manuscript was written by Gustavo Monteiro Costa Sbampato Resende and Túlio Caetano Guimarães and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

DATA AVAILABILITY

All data generated or analysed during this study are included in this published article [and its supplementary information files].

ARTIGO 3 - VALORIZAÇÃO DE RESÍDUOS AGRÍCOLAS DE FEIJÃO PARA PRODUÇÃO DE COMPÓSITOS POLIMÉRICOS

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Valorization of bean agricultural wastes for the production of polymeric composites

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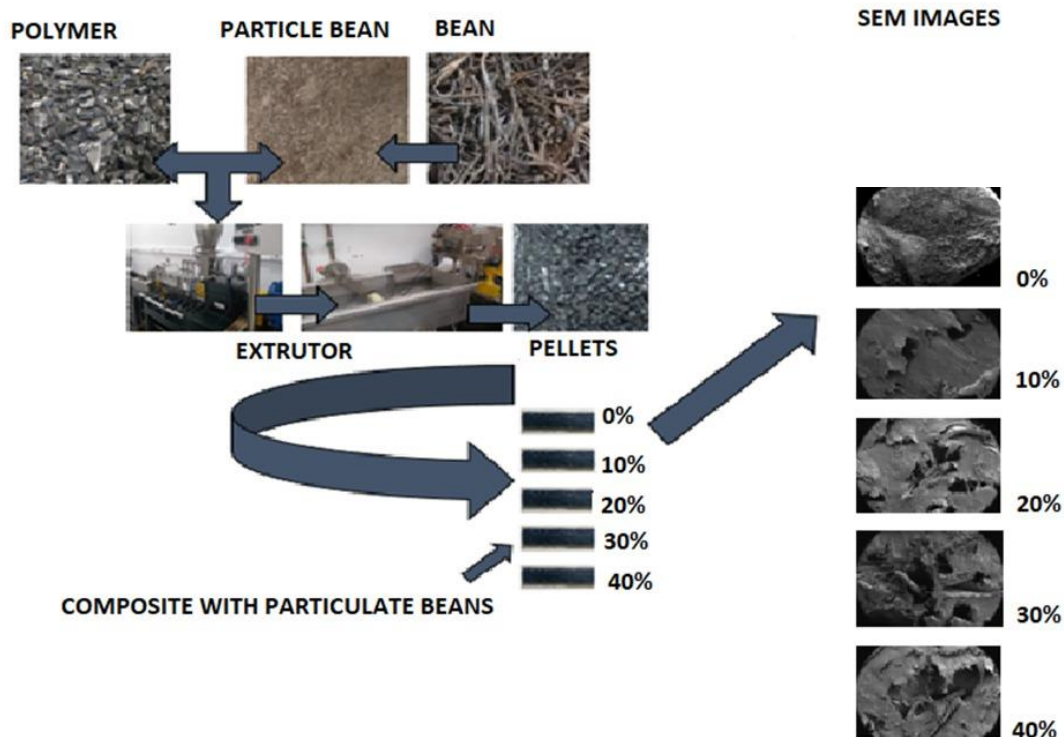
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Abstract

The objective of this study is to evaluate the characteristics of polymeric composites containing different levels of addition of bean residue. To this end, agricultural residues were first reduced to particles and characterized "in natura" through tests for moisture content, bulk density, content of extractives, lignin and ash and by thermogravimetry technique. Then, the particles were dried and selected based on their granulometric fractions to make low-density polyethylene (LDPE) composites with addition levels of 0, 10, 20, 30 and 40% bean residues. The polymeric material and the bean waste particles were hot-extruded to obtain strands and then pellets; the resulting materials were then molded and hot-pressed. After fabrication, the specimens were subjected to physical testing for humidity, density, water absorption, and flammability and to mechanical testing for tensile strength. Transmission electron microscopy (TEM) also was performed. The results showed that the lignocellulosic material had decreased density and mechanical properties and increased water absorption properties after 24 h of immersion, and the moisture content in the samples increased as a function of bean waste substitution level in the polymer composite materials. These results may be related to the intrinsic chemical characteristics demonstrated by this material in the physicochemical characterization: low density and low contents of holocellulose, lignin and extractives. The mechanical properties were also influenced by the pores created by the bean particles, which may have contributed to the creation of larger zones of weakness in the samples.

Keywords: Byproducts, LDPE, flammability.

Graphical Overview



1. Introduction

Production of polymeric items containing lignocellulosic materials has been increasing in the last ten years in several sectors of the world economy. Common and everyday materials produced from these components are pergolas, decks, furniture, decoration items, brises, baseboards, materials for the automotive industry, among others. (Carus et al. 2015; Chaudemanche et al. 2018).

Large amounts of polymeric waste are, however, generated from the production of these composites or other polymeric materials, and the improper disposal of these materials causes environmental pollution, especially in riverbeds and oceans. Therefore, there is a need to decrease the production and use of nonrenewable products or, at the very least, promote greater recycling of these materials. Brazil, for instance, was responsible for generating 11.3 million tons of polymeric wastes in 2016, and only 1.28% of these total polymers were recycled (Kaza et al. 2018).

Although the physical, mechanical, and chemical properties of low-density polyethylene (LDPE) are compatible with widespread industrial use, it can accumulate in the environment as a pollutant. In this context, the use of recycled polymeric materials is a potential alternative for reducing the environmental impacts resulting from the manufacturing of polymeric materials and reverse logistics after polymer use (Thomas et al. 2022; Kaza et al. 2018).

Another economical option with less environmental impact that has been growing in recent years in the polymeric composite sector is the use of these polymeric materials in conjunction with lignocellulosic wastes, that is, products manufactured by injection-molding or extrusion-disposal of discontinuous granular thermoplastic polymers with the addition of fibers (Brenken et al. 2019). Such insertions solve two bottlenecks presented by these "in natura" materials: the low stiffness of some polymers and the high water absorption of most plant fibers (Mertens et al. 2017).

Several researchers have studied, in this context, the use of biomass wastes from different agricultural branches in conjunction with polymers, and they have highlighted combinations of hybrid polymer composites with the following plant fibers: bamboo (Subash et al. 2022), pinecone (Şahinöz et al. 2022), sugarcane bagasse (Madhoushi et al. 2021), jute (Ganesh; Anand, 2022), hemp (Bhowmik et al. 2022), pineapple (Dilli Babu et al. 2020), banana pseudostem (Jordan and Chester 2017), coconut peel (de Araújo Veloso et al. 2021), and coffee wastes (García-García et al. 2015), with the primary objective of improving the biodegradability and chemical and mechanical properties of the composite material (Brenken et al. 2019; Peças et al. 2018).

Residues from bean plantations are among the agricultural residues with application potential still little explored in this scientific area. The Brazilian bean grain crop in 2023/2024 is projected to reach a production of almost 3.25 million tons. Bean production is accompanied

by more than 50% residue production, and these residues are usually disposed of incorrectly in nature (CONAB 2021).

Therefore, the main purpose of this research is to evaluate the physical-mechanical properties of polymeric low-density polyethylene (LDPE) matrix composites in which bean waste particles have been introduced at different polymer mass addition levels (0, 10, 20, 30 and 40%).

2. Materials and methods

2.1 Material

The bean residues used in the experiment originated from the leftover *Phaseolus vulgaris* harvest of the Pimentas farm (Lavras, Minas Gerais, Brazil) (latitude 21°15'58.5" S and longitude 45°03' 31.5" W). The residues consisted of stems and pods that were collected after natural drying. To produce the composites, the material was ground and separated according to granulometry. The particles that passed through a 40 mesh (0.42 mm) sieve and were retained on a 60 mesh (0.25 mm) sieve were selected.

The recycled low-density polyethylene (LDPE) used for the development of the composites was obtained from a recycling industry located in the city of Lavras, Minas Gerais, Brazil, and it had dimensions of 1.5 x 4.0 cm. Both materials could be fed into the extruder without pretreatment.

The bean residues and the LDPE were dried in an oven at a temperature between 50-75 °C. The drying was finished when the particles reached a moisture content between 3-4 %, a value necessary not to hinder the following procedures.

2.2 Methods

2.2.1 Materials characterization

Bean waste particles, granulometrically separated, as previously mentioned, and homogeneously distributed, aiming to homogenize the physicochemical characteristics of the

three parts of the plant, were characterized by the tests shown in Table 1. All tests were performed in triplicate.

Table 1. Characterization of the bean residues.

Test	Standard
Apparent density	NBR 14810-2 (ABNT 2018)
Moisture	NBR 14810-2 (ABNT 2018)
Extractives	NBR 14853 (ABNT 2010)
Acid-insoluble lignin	NBR 7989 (ABNT 2010)
Ash content	NBR 13999 (ABNT 2017)

The holocellulose content was obtained by percentage difference based on the other chemical constituents (Equation 1).

$$H(\%) = 100 (\%) - \text{total extractives} (\%) - \text{lignin content} (\%) - \text{ash content} (\%) \quad (1)$$

Thermogravimetric analyzes (TGA) were also performed to characterize the residues. The test was performed in an open alumina crucible, and the samples were heated from 25 to 500 °C at a nitrogen flow of 20 mL/min, with a heating rate of 10 °C/min. The degradation temperature was determined from the inflection of the baseline of the differential thermogravimetric (DTG) curve.

2.2.2 Composite production

After the characterization of the materials, the polymeric composites were produced through the gradual mass addition of bean waste particles in a low density polyethylene (LDPE) matrix, totaling five treatments. The addition levels were 0, 10, 20, 30 and 40% (de Araújo Veloso et al. 2021).

To produce the composites, 600 g of material was processed in a twin-screw extruder with a manual feed. In the extruder, this material went through seven hot zones (120 °C - 130 °C – 140 °C - 140 °C - 140 °C - 140 °C - 150 °C), generating a strand that was later cooled in water (24 ± 2 °C) and cut into small pellets that were placed in metal molds with dimensions of 120x12x3 mm (length, width and thickness). The molds were transferred to an automatic hydraulic press (MA 098) for a pressing cycle at 135 °C and 40 MPa for 15 minutes. After the samples were pressed, they were cooled in water (24 ± 2 °C) and stored in a controlled, weather-free environment (22 ± 2 °C and RH $65 \pm 5\%$) for a period of 7 days (de Araújo Veloso et al. 2021).

2.2.3 Composite characterization

Evaluation of the polymer matrix composites containing bean residues was performed by the tests presented in Table 2. All tests were performed in triplicate.

Table 2. Tests performed on the composites

Test	Standard
Tension	ASTM D638-01 (ASTM 2002)
Water Absorption	ASTM D570-98 (ASTM 2018)
Flammability	UL-94 (UL 1986)

The moisture content of the composites on a dry basis was determined by weighing them before and after thermal processing in an oven (105 ± 5 °C) for 24 h. The bulk density was measured by dividing the mass by the volume of each sample.

The flammability test was carried out with the aid of a fixed test piece and a Bunsen burner. The composites were fixed to the material and a flame was lit through the Bunsen burner. After ignition, the time for self-extinguishing of the material and whether there was dripping are

measured, in order to correlate the flammability classification according to the standard UL-94 (UL 1986).

The tensile test was carried out in a universal testing machine with a load cell of 2000 kgf, test speed of 5 mm/min and distance between the claws of 9.76 cm.

Transmission electronic microscopy (TEM) tests were also performed using a Zeiss microscope (model DSM 940^a) that belongs to the Department of Plant Pathology of the Federal University of Lavras (UFLA) to evaluate the region of tensile rupture. To this end, the samples were dried in an oven and then plated with gold.

2.2.3 Experimental design

The experimental design was entirely randomized with 5 treatments and 3 replicates. Linear regression tests and analysis of variance (ANOVA) were performed to compare and evaluate the effect of bean residue addition on the polymeric matrices.

3. Results and Discussion

3.1 Bean residue characterization

Table 3 shows the results of the chemical and physical properties of the "in natura" materials, namely, bean particles.

Table 3. Chemical characterization of bean residue

Moisture (%)	Apparent density (g/cm ³)	Extractives (%)	Lignin (%)	Ashes (%)	Holocellulose (%)
9.98 ^{(0.83)*}	0.24 ^(0.03)	8.16 ^(1.60)	8.13 ^(0.79)	16.94 ^(0.43)	56.55 ^(3.97)

*Standard deviation of means

The measured moisture value for the bean residue was 9.98%. This value is higher than the 4% value reported for coffee parchment (Scatolino et al. 2017), and since the lignocellulosic and polymeric material particles were dried to a moisture content of 3-4% before the production of the composites, both materials had a moisture content lower than 5%, close to that

recommended by Barbosa et al. (2019), who stated that a 5% moisture content in lignocellulosic materials is ideal for composite applications because it avoids gas evaporation and the appearance of bubbles.

The measured apparent density for the bean residue was 240 kg/m^3 ; since the value is lower than 500 kg/m^3 , it is considered a low-density material according to the Technological Research Institute (IPT 1985). This value agrees with that obtained in other studies of the same residue (Miranda et al. 2022a). It is also equal to the particle density of *Pinus taeda* (Miranda et al. 2022b) and is lower than the apparent density obtained by Wong et al. (2020) for sugarcane bagasse (620 kg/m^3). According to Iwakiri and Trianoski (2020), low density values are desirable for composite manufacturing because a greater number of particles is present within the same volume of the multiphase material, and the resulting material is lighter.

For extractives and lignin, hydrophobic compounds of low molecular weight in the bean residues presented respective values of 8.16% and 8.13%. The values for lignin were lower than those obtained for soybean residues (22.04%) (Borges et al. 2022) and coffee wastes (29.28%) (Santos et al. 2022). The values of extractives were lower than those obtained from sugarcane bagasse (19.59%) (Soares et al. 2017) and soybean residues (13.69%) (Borges et al. 2022). These data reveal that the use of this product in polymeric matrices is favorable (Iwakiri and Trianoski 2020).

The ash content was 16.94%, and although this is a relatively high value compared with other lignocellulosic materials, such as cocoa residue (3.17%) (de Araújo Veloso et al. 2021) and bamboo fibers (0.22%) (Gomes et al. 2021), there are no literature reports on the influence of this component on polymeric composites (Iwakiri and Trianoski 2020).

The holocellulose value for the bean residue was 56.55%, which is lower than that reported for corn cobs (76.70%) by Scatolino et al. (2013). Due to the hydroxyl groups (OH) present in holocellulose, the resulting lignocellulosic materials are highly hydrophilic. This can hinder the

use of these materials in various applications by negatively impacting physical properties related to water and moisture absorption (Iwakiri and Trianoski 2020).

The results of the thermogravimetric analysis (TGA) and derivative thermogravimetric analysis (DTG) of the bean residues are presented in Figure 1.

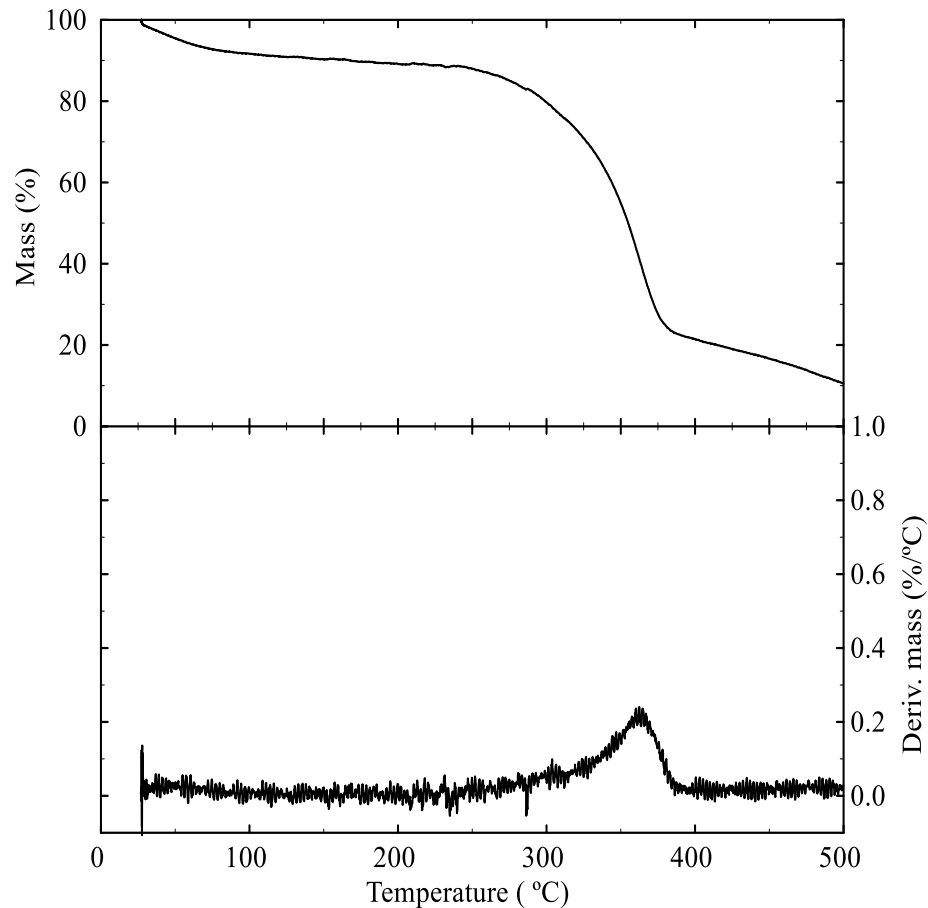


Fig. 1. TGA and DTG curves of the bean residues.

Initially, a 9.01% loss of adsorbed water is observed below 120 °C. Between 200 and 400 °C in the TGA plot, there is a region of holocellulose decomposition, corresponding to 67.66% of the composition. A peak in the decomposition of these components is noted at ~350 °C in the DTG curve. Lignin decomposes between 400 and 500 °C (10.92%), and above this temperature, the mass loss is negligible (Acchar et al. 2013). The decomposition of these lignocellulosic components is consistent with the chemical characterization shown in Table 3.

3.2 Physical properties of the composites

The results of the physical properties, moisture (W), water absorption at 2 h (WA2 h) and 24 h (WA24 h) after water immersion and bulk density (ρ) are displayed in Figure 2. The equilibrium moisture between the relative humidity and room temperature of the composites increased linearly, with a significant R^2 coefficient of 0.7914 and an Fc of 0.7914, from 0.16% in the reference sample to 3.26% in the sample with 40% beans, as observed in Figure 2a.

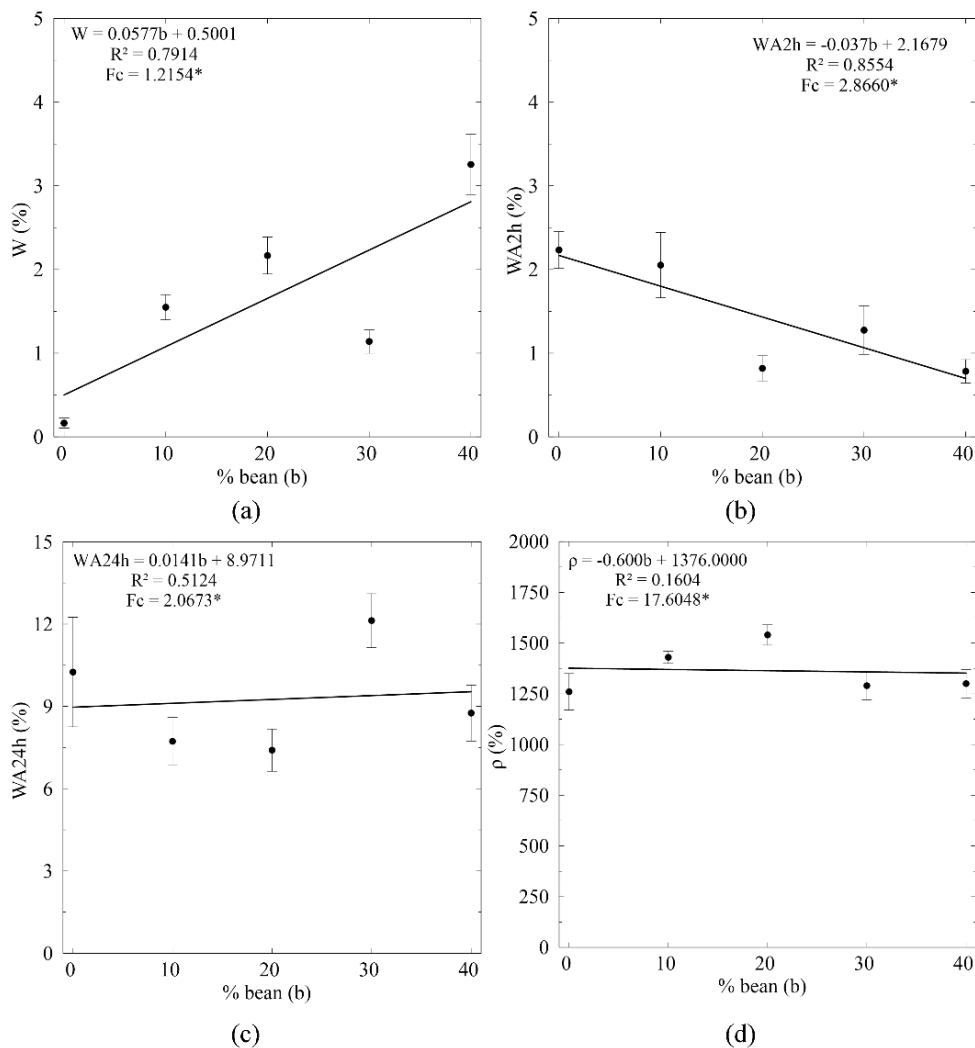


Fig. 2. Moisture (a), water absorption after 2 h (b), water absorption after 24 h (c) and bulk density of the composites (d). * Significant regression analysis at 5% significance.

The water absorption after 24 h of immersion (Figure 2c) of the composites also followed a linear trend in growth as a function of increasing lignocellulosic residues in the polymeric com. However, the linear regression coefficient R^2 was smaller (0.5124), and the coefficient of analysis of variance was 2.0675. This trend is similar to that found by de Araújo Veloso et al. (2021), in which the moisture of the composites in the study varied from 0.03% in the LDPE reference sample to 2.68% in the sample with 40% cocoa waste and the water absorption after 24 h varied from 0.17% in the reference sample to 2.68% in the sample containing the highest amount of lignocellulosic waste.

This may be related to the holocellulose content found in the lignocellulosic materials (Table 3). Lignocellulosic materials are hydrophilic due to the hydroxyl groups (OH) present in holocelluloses. This characteristic may restrict the use of these materials for several applications (Coutinho et al. 2003; Iwakiri and Trianoski 2020).

After 2 h of immersion (Figure 2b), an opposite trend was observed, meaning that initially, as the polymer had high hydrophobicity, these characteristics prevailed over short periods. At longer periods, however, the hydrophilicity of the bean particles caused an increase in water absorption (Adegoke and Bello 2015).

In the results shown in Figure 2d, a slight decrease in bulk density is noted with the increase in bean particles in the multiphase material, but it is not significant at the level of linear regression and analysis of variance. A similar trend was found by de Araújo Veloso et al. (2021) after cocoa waste was incorporated into LDPE matrices, and this may be related to the lower density of the waste in relation to the polymer. LDPE has a density ranging between 912 and 925 kg/m³, while lignocellulosic materials have much lower densities (240 kg/m³), allowing the resulting multiphase materials to be lighter (Coutinho et al. 2003).

3.3 Flammability of the composites

The results of the flammability test can be found in Table 4.

Table 4. Flammability test results.

Addition	Time to self-extinguish after ignition (s)	Was there drip?	UL 94 Classification
0	405	Yes	H-B
10	321	Yes	H-B
20	285	Yes	H-B
30	191	Yes	H-B
40	155	Yes	H-B

Although all composites showed equal flammability ratings (H-B, highly combustible), the materials containing more bean residue impacted the time to self-extinguish the fire, meaning that such materials are more flammable than the polymers and therefore impair flame spread resistance (UL-94, UL 1986).

Kim et al. (2018) claimed that the high concentrations of levoglucosan generated with the thermal decomposition of lignocellulosic fibers can increase flammability levels. This fact was also suggested by Chai et al. (2012) when they compared the flammability of polymer composites containing glass fibers and composites with flax fibers. The authors observed that composites containing natural fibers have higher heat release rates and higher burning rates than those containing glass fibers.

The low fire resistance of natural fibers and consequently the higher flammability of these materials can hinder their use in environments with stricter safety regulations.

3.4 Mechanical and microstructural characterization of the composites

From the tensile test results, it was obtained the following properties: modulus of elasticity (E), modulus of rupture (σ) and tenacity (T), that can be seen in Figure 3.

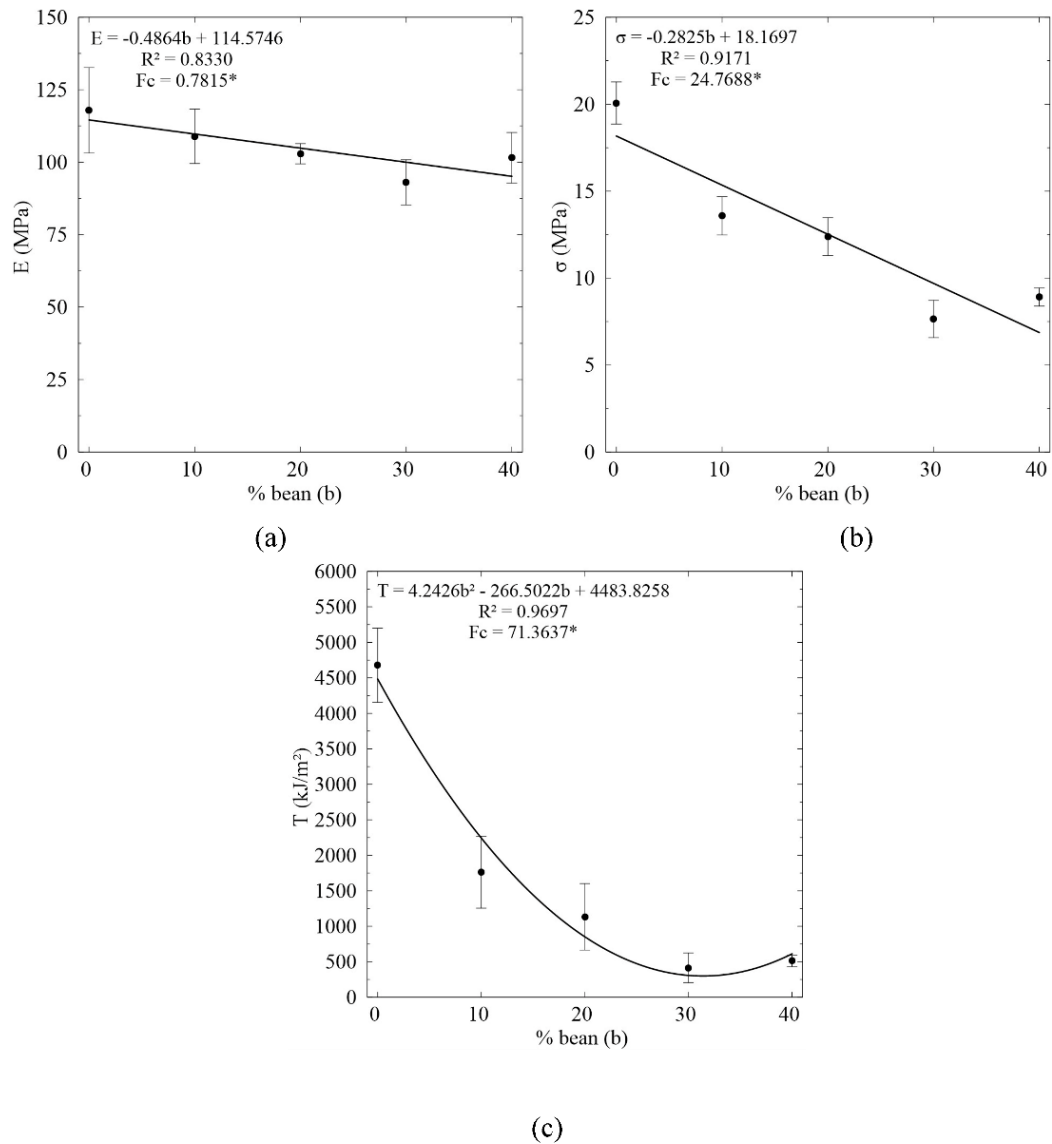


Fig. 3. Result of the tensile tests: modulus of elasticity (E) (a), modulus of rupture (σ) (b) and tenacity (T).

The E ranges from 102 to 240 MPa; the σ of this material is reported to have values between 6.9 and 16 MPa; the value for the reference sample was compatible with those reported for it in the literature (Coutinho et al. 2003).

The insertion of bean residues led to a significant decrease in the E and σ values, from 117.87 MPa to 101.50 MPa and 20.07 MPa to 8.97 MPa, respectively, in the reference sample for the sample with higher lignocellulosic material content (Fig. 3a and b). This decrease may

be related to the low concentration of cellulose found in the bean particles compared with other lignocellulosic wastes, which acts to reinforce the composites (Table 3) (Oliveira et al. 2017). The tenacity (T) values also decreased as the lignocellulosic residues were added (Fig. 3c) (4678.34 to 511.16 kJ/m²). The same behavior was reported in literature for high impact polystyrene composites (HIPS) reinforced with green coconut shell fibers (Pereira et al. 2017). For Veloso et al. (2021), the reduction in tenacity values is associated with intrinsic factors to both materials (polymer and waste). In addition, low tenacity values can directly affect the impact resistance of the composite (Coutinho et al. 2003; Pereira et al. 2017).

Low degrees of interaction or degradation at the interface between the fibers and matrices may also have influenced the decrease in the mechanical property values of the composites (Mertens et al. 2017).

This tendency also may be related to the greater number of pores in the samples, as confirmed by TEM analysis (Fig. 4). The fracture regions in the samples show a nonhomogeneous distribution of bean materials at the points of weakness. Voids are also present, resulting from the detachment and removal of the fibrous residue grain, indicating that there are weak interactions between the reinforcement and the matrix. In this sense, stress transfer is reduced when unfilled pores are present at the interfaces and at some imperfections, which aids in the propagation of cracks in the material (Mertens et al. 2017).

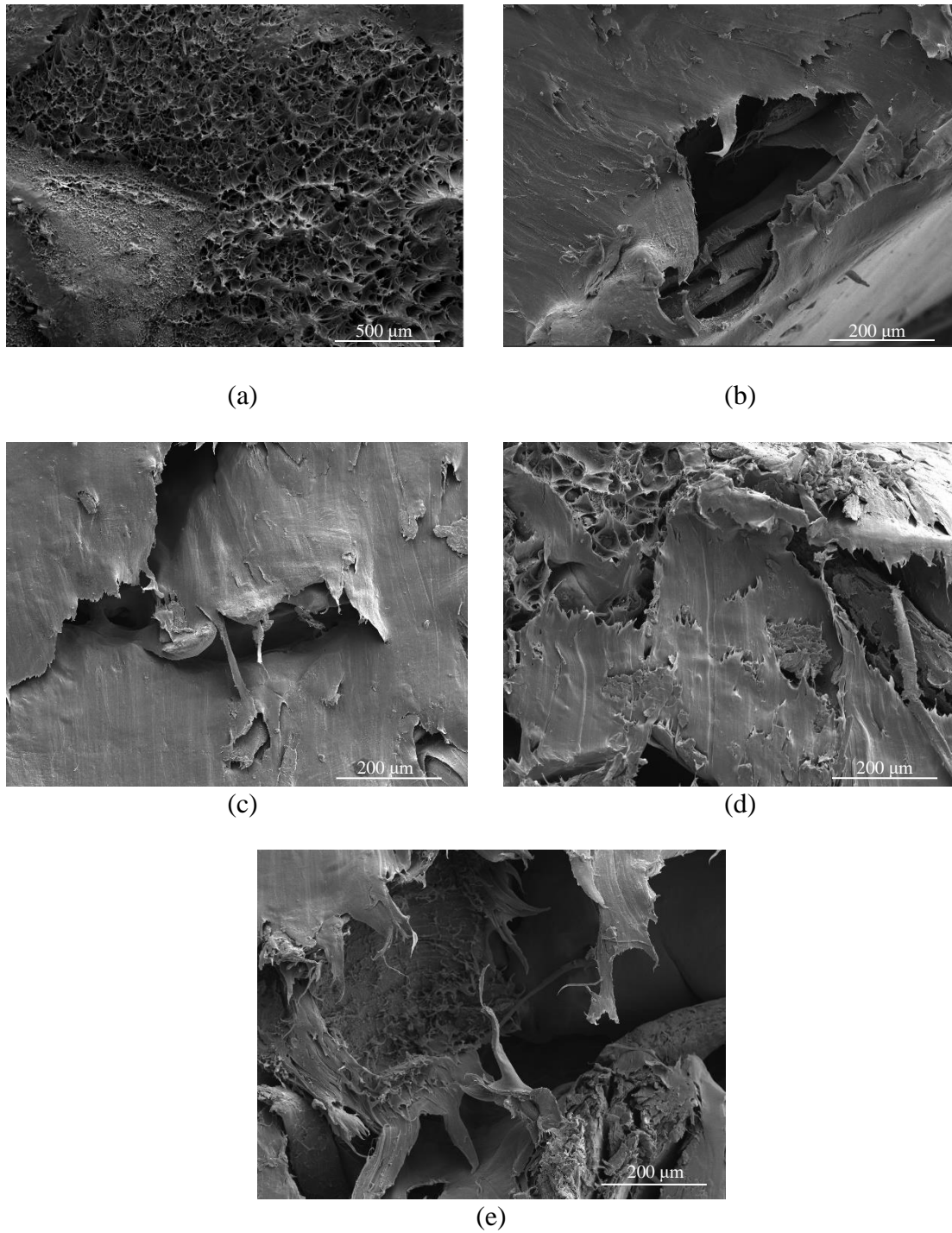


Fig. 4. TEM images of materials: reference (a) and composites with bean particles addition levels of 10% (b), 20% (c), 30% (d) and 40% (e).

4. Conclusions

The objective of this study was to analyze the influence of bean particles incorporation on the physical, mechanical and microstructural properties of polymer composites.

Regarding physical properties, the results showed that the incorporation of lignocellulosic material caused uniformity in the apparent density of the panels. Furthermore, moisture and water absorption at 24 hours increased proportionally to the higher polymer substitution content per residue, 0.16 to 3.26% and 8.76 to 10.25%, respectively, due to the holocellulose content of waste (56.55%). The bean residue also contributed to faster flame propagation in the flammability test.

Regarding the mechanical properties arising from the tensile test, there was a downward trend in all properties analyzed, modulus of elasticity 117.87 to 101.50 MPa, modulus of rupture 20.07 to 8.97 MPa and tenacity, 4678.34 to 511.16 kJ/m², with the incorporation of bean residues. This may be related to low compatibility between the matrices, interface degradation and a large number of voids in the samples confirmed in TEM analyses.

Therefore, it was not possible to prove the feasibility of applying polymer composites reinforced with bean waste, requiring further studies with new formulations, particle pre-treatments and other parameters to overcome the problems analyzed.

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TERCEIRA PARTE

1 CONSIDERAÇÕES FINAIS

Esta tese teve como objetivo analisar a viabilidade do reaproveitamento de caules e vagens de feijão (*Phaseolus vulgaris*) na produção de três tipos de materiais compósitos: painéis aglomerados, compósitos de gesso e compósitos poliméricos. Os principais resultados demonstraram que:

- Os resíduos de feijão apresentaram baixos valores de densidade aparente (0,24 g/cm³), extrativos (8,16%), lignina (8,13%) e holocelulose (56,55) além de alto teor de cinzas (16,94 %);
- Em painéis aglomerados, produzidos por meio de diferentes níveis de substituição em massa (0%, 25%, 50%, 75% e 100%) da madeira de *Pinus oocarpa* por partículas do subproduto, a incorporação desses resíduos resultou em uniformização da densidade aparente nas amostras analisadas. Além disso, observou-se aumento na razão de compactação, absorção de água e inchamento em espessura, com redução proporcional das propriedades mecânicas conforme o aumento do teor de substituição da madeira pelos resíduos; entretanto, as propriedades mecânicas atenderam as normas até determinados teores de substituição;
- Em compósitos de gesso com diferentes teores de substituição em massa (0%, 2,5%, 5%, 7,5% e 10%) do gesso pelos resíduos, verificou-se aumento do isolamento térmico e acústico nos compósitos contendo resíduos de feijão. Adicionalmente, em teores de substituição de até 5% do gesso pelo material lignocelulósico, constatou-se diminuição da umidade e aperfeiçoamento na maioria das propriedades mecânicas analisadas;
- Em compósitos poliméricos produzidos com diferentes teores de substituição em massa (0%; 10%; 20%; 30% e 40 %) de polietileno de baixa densidade (PEBD) reciclado por partículas de resíduos de feijão, por outro lado, o material lignocelulósico ocasionou uma diminuição da densidade e das propriedades mecânicas e aumento das propriedades de absorção de água após 24 h de imersão e teor de umidade; estes resultados foram correlacionados aos vazios, trincas e pontos concentradores de tensão encontrados nas micrografias realizadas. Além disso, no ensaio de inflamabilidade, os resíduos de feijão contribuíram para uma maior propagação de chamas.

Dessa forma, a pesquisa apresentou resultados relevantes para o desenvolvimento de processos menos impactantes ao meio ambiente e a geração de produtos de maior valor

agregado, principalmente nas indústrias moveleiras, da construção civil e de construção de materiais pré-moldados como placas, *decks*, brises, dentre outros.

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