Comparative Mechanical Characterization of Recycled PVC and Wood–Plastic Composites

Caracterización mecánica comparativa de compuestos de PVC reciclado y madera-plástico

Caracterização Mecânica Comparativa de PVC Reciclado e Compósitos de Madeira-Plástico

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Summary. - Recycled polymers offer opportunities for circular material use, yet their mechanical performance is often limited by feedstock variability. This study provides a controlled comparison of neat recycled PVC and WPC (PVC + 20 wt.% wood flour) processed under identical extrusion and compression-molding conditions. Tensile, flexural and hardness tests were conducted according to ASTM standards, and results are reported as mean ± standard deviation (n = 5). The WPC exhibited modest but measurable increases in tensile strength (~12%), flexural strength (~8%), and Shore D hardness (~8.5%), while tensile and flexural moduli remained statistically comparable between the two materials. Flexural modulus exceeded tensile modulus for both materials, consistent with surface-dominated stress distributions in bending. The findings demonstrate that incorporating 20 wt.% wood flour into recycled PVC can enhance selected mechanical properties without compromising stiffness, offering a performance profile consistent with material-substitution pathways in circular-economy strategies. The study also highlights the influence of recycled feedstock variability and identifies the need for future microstructural characterization to confirm the hypothesized deformation and failure mechanisms.

Keywords: wood–plastic composite, recycled PVC, tensile tests, flexural tests, hardness, ASTM standards, mechanical properties, sustainability.

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***Resumen. -** Los polímeros reciclados ofrecen oportunidades para el uso circular de materiales, pero su rendimiento mecánico suele estar limitado por la variabilidad de la materia prima. Este estudio proporciona una comparación controlada de PVC reciclado puro y WPC (PVC + 20 % en peso de harina de madera) procesados bajo condiciones idénticas de extrusión y moldeo por compresión. Se realizaron ensayos de tracción, flexión y dureza según las normas ASTM, y los resultados se presentan como media ± desviación estándar (n = 5). El WPC mostró incrementos modestos pero medibles en la resistencia a la tracción (~12 %), la resistencia a la flexión (~8 %) y la dureza Shore D (~8,5 %), mientras que los módulos de tracción y flexión se mantuvieron estadísticamente comparables entre ambos materiales. El módulo de flexión superó al módulo de tracción en ambos materiales, lo que concuerda con las distribuciones de tensión dominadas por la superficie en la flexión. Los hallazgos demuestran que la incorporación de un 20 % en peso de harina de madera al PVC reciclado puede mejorar ciertas propiedades mecánicas sin comprometer la rigidez, ofreciendo un perfil de rendimiento consistente con las vías de sustitución de materiales en las estrategias de economía circular. El estudio también destaca la influencia de la variabilidad de la materia prima reciclada e identifica la necesidad de una caracterización microestructural futura para confirmar los mecanismos de deformación y falla hipotetizados.*

***Palabras clave:** compuesto de madera y plástico, PVC reciclado, ensayos de tracción, ensayos de flexión, dureza, normas ASTM, propiedades mecánicas, sostenibilidad*

***Resumo**. **-** Polímeros reciclados oferecem oportunidades para o uso circular de materiais, porém seu desempenho mecânico é frequentemente limitado pela variabilidade da matéria-prima. Este estudo apresenta uma comparação controlada entre PVC reciclado puro e WPC (PVC + 20% em peso de farinha de madeira) processados sob condições idênticas de extrusão e moldagem por compressão. Ensaios de tração, flexão e dureza foram conduzidos de acordo com as normas ASTM, e os resultados são apresentados como média ± desvio padrão (n = 5). O WPC exibiu aumentos modestos, porém mensuráveis, na resistência à tração (~12%), resistência à flexão (~8%) e dureza Shore D (~8,5%), enquanto os módulos de tração e flexão permaneceram estatisticamente comparáveis entre os dois materiais. O módulo de flexão excedeu o módulo de tração para ambos os materiais, o que é consistente com a distribuição de tensões predominantemente superficiais na flexão. Os resultados demonstram que a incorporação de 20% em peso de farinha de madeira ao PVC reciclado pode aprimorar propriedades mecânicas selecionadas sem comprometer a rigidez, oferecendo um perfil de desempenho consistente com as vias de substituição de materiais em estratégias de economia circular. O estudo também destaca a influência da variabilidade da matéria-prima reciclada e identifica a necessidade de caracterização microestrutural futura para confirmar os mecanismos de deformação e falha hipotetizados.*

***Palavras-chave:** compósito madeira-plástico, PVC reciclado, ensaios de tração, ensaios de flexão, dureza, normas ASTM, propriedades mecânicas, sustentabilidade*

1. Introduction. - Global plastic production exceeds 300 million tons annually, driven by versatility, durability, and low production cost [1], [2], [3]. However, the environmental burden of plastic waste, particularly its persistence, non-renewable origin, and low biodegradability, has become a critical global concern [4]. Plastic debris contaminates terrestrial and aquatic ecosystems, adversely affecting biodiversity and human health [5]. As pressure mounts to reduce environmental footprints, researchers and industries are increasingly turning to recycling and composite technologies to extend the utility of plastic waste [6].

Among commonly recycled thermoplastics, polyvinyl chloride (PVC) stands out due to its extensive use in construction, packaging, and consumer goods. PVC exhibits desirable characteristics such as flame retardancy, corrosion resistance, and dimensional stability. However, its recycling is complicated by the presence of additives like plasticizers, stabilizers, and residual contaminants that can hinder reprocessing and reduce mechanical integrity [7], [8]. Still, the abundance of post-consumer PVC waste, particularly from pipes, cables, and siding, offers a valuable feedstock for secondary applications if properly reformulated [9].

One strategy to potentially enhance the properties or sustainability profile of recycled PVC involves hybridizing it with bio-based fillers, such as wood flour, to create wood–plastic composites (WPCs). WPCs are typically fabricated by melt-compounding wood flour with thermoplastics, followed by extrusion or molding [10]. This approach leverages the natural stiffness and renewability of lignocellulosic biomass while potentially reducing dependence on virgin polymers. Moreover, WPCs support circular economy principles by valorizing both plastic and biomass waste streams [11], [12].

WPCs are increasingly used in decking, fencing, automotive interiors, and furniture [13]. However, their mechanical performance is influenced by many factors, including wood particle size and morphology, polymer–filler ratio, processing conditions (like mixing methods and temperature profiles), and interfacial adhesion [10], [14], [15]. Generally, adding wood flour increases composite stiffness and hardness but can impact ductility and strength depending on the specific formulation and interface quality. This performance balance is often attributed to the inherent incompatibility between hydrophobic polymer matrices (like PVC) and hydrophilic cellulosic fillers, potentially leading to stress concentrations and microvoids at the interface [16], [17], [18]. The quality of the recycled matrix itself can also influence final composite properties [8], [19].

Furthermore, studies have demonstrated that chemical treatment of wood flour or the use of coupling agents can substantially affect composite performance [20]. For instance, coupling agents and compatibilizers can improve adhesion between filler and matrix, potentially resulting in higher strength and moisture resistance [21], [22], [23]. Similarly, the thermal stability of WPCs depends on the nature and content of the lignocellulosic material used [24]. Such parameters must be carefully optimized to tailor composites for specific end-use applications.

Despite numerous studies on WPCs (often based on polyolefins) and recycled PVC separately [10], [19], [25], few have offered a systematic mechanical comparison between recycled PVC and its corresponding WPC variant under identical processing and testing protocols. This study aims to address this gap by presenting a controlled, comparative investigation of key mechanical properties – specifically tensile, flexural, and Shore D hardness of recycled PVC and its 20% wood-filled composite under consistent, ambient conditions.

2. Material and Methods. -

2.1. Materials. - Recycled PVC pellets (derived from post-consumer pipes and sheets) and kiln-dried hardwood sawdust (wood flour, particle size <250 μm) were procured. The wood flour was further dried at 80°C for 30 minutes just before use to remove any leftover moisture content. No additional additives or compatibilizers were introduced during reprocessing and therefore, the material reflects a heterogeneous mixture of commercial uPVC formulations typical of construction waste with the composition unknown.

2.2. Composite Fabrications. - Formulations containing 0% (PVC) and 20% wood flour by weight were dry-blended (WPC). Compounding was performed using a co-rotating twin-screw extruder (L/D = 40:1) with a screw speed of 100 rpm and barrel zone temperatures set between 150–170°C, consistent with typical processing windows for PVC-based WPCs [10]. Torque and melt pressure were monitored continuously to ensure process stability [29]. The extrudate was pelletized (diameter ≈ 3 mm) and subsequently compression molded at 160°C under 5 MPa pressure for 10 minutes into sheets approximately 3 mm thick and released hot. The molded sheets were allowed to cool at room temperature for 2 hours. Post-cure annealing was conducted at 80°C for 2 hours to minimize residual stresses [30]. Test specimens were precisely laser cut according to ASTM D638 Type I (tensile), ASTM D790 (flexural), and ASTM D2240 (hardness) dimensions [26], [27], [28].

2.3. Mechanical Testing. - All mechanical tests were conducted in a controlled ambient laboratory environment maintained at 23 ± 2°C and 50 ± 5% Relative Humidity (RH), logged using an environmental chamber compliant with ISO 291 [31]. For each material condition (PVC and WPC), five tensile specimens (n = 5), five flexural specimens (n = 5), and five hardness specimens (n = 5) were tested in accordance with the respective ASTM standards. All specimens were produced from the same compression-molded sheet batch to ensure consistency. Prior to testing, specimens were inspected for machining defects, edge cracks, or dimensional deviations greater than ±1%. One PVC tensile specimen and one WPC flexural specimen were rejected due to visible edge chipping from laser cutting and were replaced to maintain the required sample size.

Tensile tests: Performed according to ASTM D638 (Type I specimens) using a universal testing machine at a crosshead speed of 5 mm/min [26]. Strain was measured accurately using an extensometer [7]. Young’s modulus, tensile strength, and elongation at break were determined.

Flexural tests: Conducted according to ASTM D790 using a three-point bending setup [27]. The support span-to-depth ratio was maintained at 16:1, and the crosshead speed was 2 mm/min [18]. Flexural modulus and flexural strength were calculated.

Hardness tests: Measured according to ASTM D2240 using a Shore D durometer mounted on an operating stand to ensure perpendicularity and consistent load application [28]. Measurements were taken after a dwell time of 15 seconds. Five indentations were made on each specimen at different locations [3]. None of the samples were rejected.

Data acquisition systems sampled load and displacement/strain data at 1 kHz, filtered using a 10 Hz low pass filter, to generate high-resolution stress–strain curves. Load cells and extensometers were calibrated per ASTM E4 and standard procedures prior to testing series.

3. Results. -

3.1. Tensile Behavior. - The uniaxial tensile stress vs strain curve for a typical PVC and WPC sample is illustrated in Figure 1. The stress vs strain curve of PVC is illustrated with a solid blue line whereas that of WPC is illustrated with a dashed red line. The tensile stress–strain curves in Figure 1 show a typical elastic region followed by a short yield-like transition without a well-defined plateau for both materials, indicating semi-ductile behavior. Neither PVC nor WPC exhibited classical strain hardening; instead, both curves rose monotonically until reaching their respective maximum stresses, followed by an abrupt load drop, characteristic of polymer composites with limited plastic deformation. The PVC curve shows a smoother transition to failure, while the WPC curve displays a slightly steeper post-yield slope, consistent with modest reinforcement from wood flour.

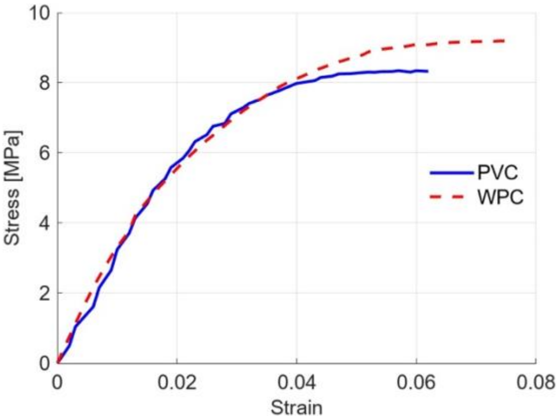

Figure I. The uniaxial tensile stress vs strain curves for neat, recycled PVC and WPC (PVC + 20 wt.% wood flour) samples.

The tensile properties are reported as mean ± standard deviation for n = 5 specimens per material. PVC exhibited an elastic modulus of 395 ± 32 MPa. Its ultimate tensile strength was measured at 8.2 ± 0.85 MPa, with an elongation at break of 6.2 ± 0.13%.

The incorporation of 20% wood flour into PVC to create the WPC resulted in notable changes. The elastic modulus remained comparable at approximately 398 ± 27 MPa. However, the tensile strength increased to 9.2 ± 1.1 MPa, representing an approximate 12% increase compared to neat PVC. The WPC sample showed a slightly increased elongation at break of 7.5 ± 0.18%.

The observed increase in tensile strength for the WPC, despite similar stiffness, is likely attributed to the reinforcing effect of the cellulose fibers within the wood flour. These fibers may contribute to load-bearing capacity, particularly after the PVC matrix yields, enhancing the composite's overall strength before fracture. The effect on ductility requires careful consideration of failure modes.

3.2. Flexural Behavior. - The three-point bending stress vs strain curves for a typical PVC and WPC sample is illustrated in Figure 2. The stress vs strain curve of PVC is illustrated with a solid blue line whereas that of WPC is illustrated with a dashed red line. The flexural stress–strain curves in Figure 2 show a linear elastic region up to approximately 2–2.5% strain for both materials, after which the curves begin to deviate due to matrix microcracking and the onset of tensile-side yielding typical of thermoplastic composites under bending. Neither material exhibited a distinct yield plateau; instead, the curves increased steadily to a peak flexural stress before showing a sharp drop associated with catastrophic failure. The WPC curve demonstrates slightly higher peak stress and marginally improved strain tolerance.

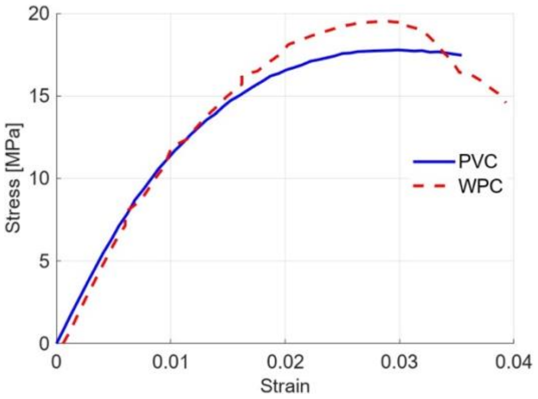

Figure II. The three-point bending stress vs strain curves for neat recycled PVC and WPC (PVC + 20 wt.% wood flour) samples

Flexural properties (n = 5 per material) are presented as mean ± standard deviation. Both PVC and WPC showed similar initial stiffness in bending, with calculated flexural moduli in the range of 1650 ± 365 MPa and 1680 ± 294 MPa, respectively. As expected, these values are substantially higher than the elastic moduli observed in tension due to the stress gradient inherent in bending.

The flexural strength of PVC was determined to be 18.1 ± 1.75 MPa. The WPC sample demonstrated a higher flexural strength, measured at 19.5 ± 1.95 MPa, approximately 8% greater than the PVC.

The strain at which failure or substantial load drop occurred in bending was approximately 0.035 ± 0.009 for PVC and slightly higher, around 0.038 ± 0.011, for WPC. This suggests the WPC could withstand slightly more bending deformation before failure compared to PVC under these test conditions.

The tensile and flexural test results indicate that while the incorporation of 20% wood flour does not alter the stiffness (Young's/Flexural Modulus) compared to PVC, it enhances both the tensile and flexural strength. This improvement is attributed to the reinforcing contribution of the wood fibers within the composite structure. The WPC also showed comparable or slightly increased strain tolerance before failure in bending.

3.3. Hardness Measurements. - The Shore D hardness values are presented in Table 1.

	Shore D Hardness									
Sample No.	**PVC**					**WPC**				
1	29	30	30	29	28	33	32	31	32	32
2	31	29	30	30	29	31	32	34	32	32
3	30	29	30	29	30	31	32	33	32	32
4	30	29	30	29	30	32	30	32	32	32
5	30	29	30	30	29	32	32	33	32	32

Table I. The Shore-D harness for neat, recycled PVC and WPC (PVC + 20 wt.% wood flour) samples.

Shore D hardness measurements showed a consistent increase with the addition of wood flour. This represents an 8.5% increase, paralleling trends sometimes observed with increased stiffness or filler content. The hardness enhancement likely results from the presence of the harder wood particles and potentially restricted polymer chain mobility near the filler surface, consistent with literature findings [3], [10].

Property	**Unit**	**PVC (mean ± SD)**	**WPC (mean ± SD)**	**n**
Young’s modulus	MPa	395 ± 32	398 ± 27	5
Tensile strength	MPa	8.2 ± 0.85	9.2 ± 1.10	5
Elongation at break	%	6.2 ± 0.13	7.5 ± 0.18	5
Flexural modulus	MPa	1650 ± 365	1680 ± 294	5
Flexural strength	MPa	18.1 ± 1.75	19.5 ± 1.95	5
Flexural strain at failure	Unitless	0.035 ± 0.009	0.038 ± 0.011	5
Shore D hardness	–	29.60 ± 0.50	32 ± 0.74	25

Table II. Summary of results.

4. Discussion. - The observed mechanical property changes upon adding 20% wood flour to recycled PVC reflect typical composite behavior. While simple models like the rule-of-mixtures might approximate modulus trends [9], the strength properties are more complexly governed by factors such as flaw distributions (e.g., micro-voids) and, critically, the quality of interfacial adhesion between the relatively hydrophobic PVC matrix and the hydrophilic wood filler [10], [18], [21]. Poor adhesion can lead to ineffective stress transfer from the matrix to the reinforcing filler, potentially limiting the strength enhancement [20].

The flexural modulus for both materials was substantially higher than the tensile modulus, which is expected for semi-rigid polymers and wood–plastic composites. In three-point bending, the specimen experiences a strong through-thickness stress gradient: the outermost fibres carry the highest stresses while the inner core remains relatively unstressed. As a consequence, the measured stiffness is governed primarily by the behavior of the surface layers, which respond more rigidly than the bulk polymer under uniform tensile loading. Additionally, bending constrains lateral contraction more strongly than tension, reducing Poisson expansion and further increasing the apparent modulus. From a microstructural standpoint, the wood flour present in the WPC improves surface stiffness under bending because fibers located near outer surfaces engage more effectively in load transfer. In contrast, tensile testing probes the entire cross-section uniformly, including regions containing micro-voids, imperfect filler dispersion or weak polymer–filler adhesion, which collectively reduce the effective tensile modulus.

Micro-voids, potentially formed during extrusion due to moisture release from wood flour or air entrapment, can act as stress concentrators, possibly initiating cracks under tensile and bending loads [18], [29]. The increase in tensile (~12%) and flexural (~8%) strength observed here suggests some reinforcing effect from the wood fibers, but also potentially indicates non-optimal interfacial bonding, which is common in untreated WPCs [20]. The particle size and aspect ratio of the wood flour also play a significant role in determining the reinforcing efficiency [14], [15]. Although these tests were conducted in a controlled dry state, the inherent hydrophilicity of wood fillers could introduce variability or affect long-term performance under ambient humidity due to moisture sorption at the interface, potentially degrading both the filler and the interface itself [32], [33], [34].

The slightly higher strain at failure observed in bending for the WPC, compared to PVC, is not contradictory to the tensile ductility trends. This difference arises because tensile and flexural failures are governed by different mechanisms. In bending, failure initiates in the highly stressed outer surface while the neutral axis remains relatively unstressed, allowing limited redistribution of strain before catastrophic fracture. Local microcrack blunting or fiber-bridging effects in the WPC can delay surface crack propagation, permitting a slightly greater strain before failure. Under uniaxial tension, however, the entire gauge length is uniformly stressed, making the material more sensitive to internal defects such as voids, fiber pull-out sites and poor interfacial bonding. These internal imperfections promote earlier tensile fracture, even if the same material shows slightly improved surface deformation behavior in bending. Thus, the flexural strain-to-failure trend is consistent with the expected difference in dominant failure mechanisms between the two loading modes.

When interpreting the magnitude of the observed strength improvements, approximately 12% in tensile strength and 8% in flexural strength, it is important to consider their relevance within the context of typical design safety factors and target application domains. For many structural or semi-structural applications involving PVC and WPCs such as decking boards, facade components, low-load automotive interior panels, safety factors typically range from 2 to 4. Within this framework, strength increments of the order reported here may be viewed as modest in absolute terms and, in some cases, comparable to batch-to-batch variation commonly observed in recycled polymer composites. Nonetheless, these improvements remain meaningful for several reasons. First, the increases in strength occurred without compromising stiffness or hardness and without the use of coupling agents, indicating that even unmodified wood flour can contribute positively to load-bearing capacity. Second, for high-volume applications where material cost and environmental impact are key considerations, incremental gains in strength can translate to reductions in material usage, improved durability, or expanded suitability for low to medium-load components. Finally, from a sustainability perspective, demonstrating that recycled PVC can achieve enhanced performance with renewable fillers underscores the potential for performance-neutral or performance-positive material substitutions that support circular-economy principles.

It is important to emphasize that the discussion regarding micro-void formation, interfacial debonding, and potential moisture-related effects is grounded in mechanisms widely documented in the literature for PVC and WPC-based composites, rather than in direct microstructural observations from the present study. Because no microscopy or fractographic characterization was performed on the tested specimens, these interpretations should be regarded as literature-supported hypotheses rather than experimentally confirmed mechanisms. Future investigations incorporating detailed morphological characterization would be valuable for validating the proposed deformation and failure mechanisms and for establishing more definitive structure–property correlations.

This study provides comparative mechanical benchmarks that are relevant for industrial quality control and materials selection, particularly in applications such as automotive components, façade panels, and construction elements where recycled or resource-efficient materials are increasingly considered [13], [19]. Rather than making explicit environmental claims, the present work should be viewed as contributing to material substitution strategies that are broadly consistent with circular economy principles and supportive of Sustainable Development Goals (SDGs) 9 and 12, which emphasize responsible production and sustainable infrastructure development [9], [35]. Achieving enhanced performance in recycled PVC or WPC-based systems typically requires attention to interfacial engineering, such as the use of coupling agents including maleated polyolefins or silanes, as well as process optimization to reduce defects and improve fusion quality. Future research may also explore hybrid composite formulations to simultaneously improve mechanical performance and maintain or enhance the environmental benefits associated with the use of recycled and bio-based constituents [18], [20], [21], [36].

5. Conclusion. - This study presented a controlled comparative mechanical evaluation of neat recycled polyvinyl chloride (PVC) and a wood–plastic composite (WPC) containing 20 wt.% wood flour, processed via extrusion and compression molding. The results demonstrated that incorporating wood flour achieved performance enhancements consistent with a reinforcing effect:

- Stiffness: The WPC exhibited comparable stiffness (Young's modulus and Flexural modulus) to PVC.
- Strength: The WPC showed modestly enhanced tensile strength (~12% increase) and flexural strength (~8% increase).
- Hardness: A systematic and consistent increase in surface hardness was observed, with Shore D hardness improving by approximately 8.5%.
- Ductility: While tensile elongation at break was slightly higher for WPC, the composite also demonstrated a slightly higher strain at failure in bending compared to PVC.

These strength and hardness improvements are meaningful, as they confirm that PVC can accept a bio-filler without compromising mechanical integrity, highlighting a performance-positive material substitution relevant to circular economy principles.

The selection between PVC and WPC depends on specific application requirements such as, WPCs offer benefits in stiffness consistency, strength, and hardness, while utilizing wood waste for enhanced sustainability. Given the inherent heterogeneity of recycled feedstocks and the lack of coupling agents in this formulation, achieving optimal long-term performance requires further investigation into interfacial engineering and process optimization to minimize defects and moisture effects. Future research, ideally incorporating microstructural characterization (e.g., fractography), is recommended to validate the hypothesized failure mechanisms (micro-voids and interfacial debonding) and to establish definitive structure–property correlations for these sustainable composites

Data availability. - The dataset supporting the results of this study can be requested from the corresponding author.

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Author contribution:

1. Conception and design of the study
2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
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IA has contributed to: 1, 2, 3, 4, 5 and 6.

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