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(Review Article)

Crosslinked polymers in automotive applications: Challenges and recycling strategies

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Abstract

This report is aimed at investigating the recycling difficulties of crosslinked polymers used in the automotive industry. These polymers have been extensively used in products like tires, seals, and coatings due to their long, lasting nature, heat resistance, and mechanical strength. Due to their crosslinked nature, these materials tend to make recycling improbable, resulting in continuous waste accumulation. We will take a look at the various limitations and cover the challenges in converting these crosslinked materials into value added products after recycling. Additionally, this report will address the environmental concerns related to disposal and assess emerging technologies, including vitrimer-based solutions and selective bond cleaving methods, that may provide innovative solutions to these challenges and advance sustainable practices in automotive manufacturing

Key words: Recycling; Radiation-assisted recycling; Automotives; Sustainability

1. Introduction

1.1. Overview & advantages of Crosslinked Polymers

The automotive industry is considered as one of the biggest consumers of polymeric materials, typically polyurethane (PU) and vulcanised rubber. These materials are used in tires, seals, hoses, interior component and various structural parts. Crosslinking is usually employed to achieve the required high mechanical strength, heat resistance, chemical resistance and long service life. However, the three-dimensional network renders these polymers insoluble and infusible, thus making the conventional recycling methods ineffective and leading to significant waste accumulation and environment concerns.

Thermoset bulk moulding compounds (BMCs), such as polyester and vinyl ester systems, are widely used for valve covers, oil pans, and other under-hood components due to their rigidity at elevated temperatures, resistance to automotive fluids, and flame retardancy. Unlike thermoplastics, thermosets retain dimensional stability above 200 °C but cannot be remelted. Although traditionally considered non-recyclable, thermoset scrap can be ground and reused as engineered fillers, with cost analyses indicating lower material and processing costs compared to high-performance thermoplastics for high-volume production

1.2. Importance of Recycling in the Automotive Industry

Life-cycle assessments of automotive components show that lightweight composite materials can reduce fuel consumption and CO_2 emissions compared to steel, although fully recycled aluminium often has the lowest

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environmental impact among structural options. Carbon-fibre composites offer excellent specific properties but are energy-intensive to produce, underscoring the need for efficient end-of-life strategies. [2, 3]

Studies on end-of-life vehicles (ELVs) in China highlight the importance of non-metallic components, material connections, and design-for-recycling principles in improving recoverability. Key recommendations include: prioritizing recyclable materials over thermosets where feasible; reducing material diversity; designing modular, easily separable components; and minimizing hazardous substances such as lead in batteries and electronics. Integrating recycling considerations at the design stage can reduce reliance on complex dismantling processes and landfilling, aligning automotive manufacturing with circular-economy objectives. Sensitivity analyses indicate that material consumption is the dominant factor in the energy balance of component production, emphasizing the need to minimize waste during manufacturing and to promote thermoplastic composites where performance and recycling infrastructure allow.

2. Types of Crosslinked Polymers in Automotive Applications

Crosslinked polymers primarily used in automotive applications fall into three broad classes: rubbers, thermosets, and fiber reinforced thermoset composites. [1, 4]

Table 1 Classification of crosslinked polymer classes used in automotive applications, with typical chemistries, representative component uses and the implications for recylcability

Polymer class	Typical chemistries & crosslinking	Key automotive applications	Notes on recyclability
Rubber (elastomers)	Natural rubber (NR), SBR, EPDM, NBR, IIR, FKM [7]; vulcanized via sulphur or peroxide crosslinks. [9, 10]	Tires (tread, sidewall, inner liner), seals and gaskets (doors, windows, engine, transmission, HVAC), vibration damping components (engine mounts, bushings, suspension dampers. [9, 10]	Crosslinked network prevents remelting; recycling relies on devulcanization, grinding to GTR, or pyrolysis
Thermosets	Epoxy resins (amine-cured), polyurethanes (isocyanate-based), phenolics (hexamethylenetetramine-cured); irreversible 3D networks. [7, 10–13]	Structural adhesives and matrices for CFRP (battery housings, hoods, spoilers, chassis), electrical encapsulation (motor windings, sensors), flexible/rigid foams (seat cushions, headrests, thermal insulation), coatings, high-temperature components. [14-30]	Cannot be remelted; recycling via mechanical grinding, chemical depolymerization/solvolysis, or emerging dynamic-bond systems (vitrimers).
Fiber-reinforced thermoset composites	Epoxy, polyester, or vinyl ester matrices with glass, carbon, aramid, or natural fibres (flax, sisal); cured into SMC, DMC, or CFRP. [6, 23, 24, 31–36]	Body panels (hoods, roofs, fenders, spoilers), chassis and structural components, battery enclosures and housings (especially for EVs), interior panels and dashboards (natural-fiber composites) [6, 37, 38-47]	High-value fibers (carbon, glass) can be recovered via pyrolysis or solvolysis; matrix often degraded; mechanical recycling yields fillers or short-fiber reinforcements.

3. Recycling Challenges of crosslinked polymers

The recycling of crosslinked polymers is complicated by their permanent three-dimensional network structure. Unlike thermoplastics, which can be softened and remoulded repeatedly, vulcanized rubbers and thermoset polymers generally cannot be remelted after curing. Consequently, their recycling often requires mechanical size reduction, selective bond cleavage, thermal decomposition, or the development of new materials with reversible crosslinks. The major challenges are discussed below.

3.1. Permanent Crosslinked Structure

The covalent bonds formed during vulcanization or thermoset curing provide high mechanical strength, thermal stability, and chemical resistance. However, these same bonds prevent the polymer chains from flowing when heated. As a result, conventional melt-processing methods used for thermoplastics cannot be applied directly to crosslinked materials.

Grinding is therefore commonly used to convert thermoset waste and rubber into powders, granules, or short fibers. Although this approach is relatively simple, the resulting materials are generally used as low-value fillers or reinforcement agents. The original mechanical performance is difficult to recover because the polymer network remains intact and the particle–matrix interface may be weak.

3.2. Heterogeneity and Contamination

Automotive polymer waste is rarely composed of a single, pure material. Tires, seals, hoses, foams, and composite components may contain several polymer types, fillers, pigments, plasticizers, reinforcing fibers, metals, adhesives, and surface coatings. In addition, these materials may be contaminated with oils, fuels, dirt, moisture, and other chemicals during service.

This heterogeneity makes sorting and separation difficult. Incompatible polymers may form separate phases during processing, resulting in poor interfacial adhesion, reduced strength, and increased brittleness. Contaminants can also affect colour, odour, thermal stability, toxicity, and the quality of recycled products. Effective recycling therefore requires improved identification, dismantling, sorting, and cleaning before the material is processed.

3.3. Degradation of Recycled Material

Crosslinked polymers may undergo thermal, oxidative, ultraviolet, and mechanical degradation during manufacturing and service. These processes can cause chain scission, oxidation, loss of flexibility, embrittlement, and deterioration of mechanical properties. Additional degradation may occur during grinding, devulcanization, pyrolysis, or chemical treatment. In fiber-reinforced composites, recycling can also reduce fiber length and damage the fiber surface. Although carbon and glass fibers may retain part of their original strength after thermal or chemical treatment, their properties may be lower than those of virgin fibers. The recovered fibers may therefore be suitable for secondary structural or semi structural applications but not necessarily for the same high-performance application from which they originated [9, 10, 47–50].

3.4. Technical and Economic Limitations

Many advanced recycling methods require high temperatures, pressurized reactors, specialized solvents, catalysts, radiation sources, or extensive post-treatment. Chemical recycling can produce valuable oligomers, monomers, or recovered fibers, but the process may involve hazardous solvents, corrosion, complex separation steps, and high energy consumption. Thermal processes such as pyrolysis and fluidized-bed treatment may also produce char, gases, or contaminated fibers that require further treatment.

The economic viability of these methods depends on the availability and consistency of the waste stream, the value of the recovered products, transportation costs, energy requirements, and the quality of the recycled material. If the recovered product has lower performance than the virgin material, it may only be suitable for low-value applications. Therefore, laboratory-scale success does not necessarily guarantee industrial scalability or commercial feasibility.

3.5. Environmental and Regulatory Considerations

Recycling processes must be evaluated not only according to their material recovery rate but also according to their total environmental impact. Incineration can recover energy from contaminated or mixed waste, but it may generate carbon dioxide and other hazardous emissions. Pyrolysis can recover fuels, gases, carbonaceous residues, and fibers, although the environmental benefit depends on process conditions, energy sources, and the treatment of additives and emissions. A sustainable recycling strategy should therefore consider the complete life cycle of the material, including manufacturing, use, collection, transportation, processing, and final application. Design-for-recycling principles can reduce these challenges by limiting the number of polymer types, avoiding incompatible materials, reducing hazardous additives, and enabling easier dismantling and separation. Greater standardization, improved material labelling, and collaboration between vehicle manufacturers, recyclers, and material suppliers are also required to support closed-loop recycling systems [2, 3, 57–59].

Overall, the principal challenge is not simply to break down crosslinked polymers, but to recover materials with sufficient quality, safety, and economic value for reuse in automotive products. Future progress will depend on combining improved product design with selective devulcanization, chemical recycling, advanced separation, and recyclable crosslinked polymer networks.

4. Recycling Techniques

Material recycling embraces processes which keep the macromolecular structure intact, while the material is being changed into new products. In the case of crosslinked polymers, it is often necessary to break the crosslinks in order to make the material ready for further processing.[4, 53, 54].

4.1. Mechanical Recycling

Mechanical recycling typically involves the method of grinding thermoset waste until it is finely divided or consists of short fibres. These can then be used either as fillers or reinforcements in recycled composites, asphalt, or cement. The whole process is the sequence of operations comprised of the collection, sorting, crushing, and milling in order to reduce the scrap to smaller pieces. Fiber, rich fractions are utilized as reinforcements, whereas matrix, rich powders are employed as fillers. While this technique is straightforward and inexpensive, it yields products with lower mechanical properties due to short, uneven fibers. There are now some innovations such as recycled glass fibers in 3D, printed PLA composites which have displayed increased tensile strength. The addition of GFRP waste to cement composites has likewise led to higher flexural strength. Nevertheless, the main constraint of the low, value products are their limited applications[55, 56]. The recycled PU foam showed promising tensile properties and improved density, although further optimization is required before large-scale implementation.[18, 20]

4.2. Chemical Recycling

Chemical recycling refers to the process of dismantling large molecular structures into smaller molecules. These smaller molecules can then be used as chemical feedstocks or additives. This method is particularly relevant for crosslinked polymers, which are very hard to recycle through normal material recycling methods[57–59]

In chemical recycling, the process involves the rupture of crosslinked bonds to obtain monomers, oligomers, or even fibers that have not been damaged by the use of solvents, catalysts, or irradiation techniques. As a matter of example, solvolysis techniques, such as the use of supercritical methanol, can very well aim at and cut ester bonds in epoxy composites while still carbon fibers are maintained. Besides that, catalysed reactions, e. g. with ethanol and zinc chloride ($ZnCl2$) or acetic acid and aluminium chloride ($AlCl3$), by breaking certain bonds under very limited conditions, facilitate the process. On the other hand, irradiation, assisted degradation uses ultraviolet (UV), gamma, or electron beam radiation to generate the initiation of bond breaking. Although these techniques lead to the production of materials of high quality, they also present some difficulties like the use of harmful solvents, increase in the price of the process, and problems relating to the enlargement of the process.

4.2.1. Depolymerization and Devulcanization

Devulcanization is a process that breaks down the sulphur crosslinks present in vulcanized rubber. This makes it easier to reuse the material. Traditional methods, like the pan method, usually heat rubber with oils and chemicals at high temperatures for long times. However, these methods often break both crosslinks and main chain bonds indiscriminately, which can decrease the material's properties.[60]

Recent advancements in devulcanization techniques include using microwaves and ultrasonics. These methods effectively break CS bonds while preserving CC bonds. For example, Fukumori et. al [61] Presented a continuous recycling process that uses a modular screw-type reactor designed to break crosslinks in ethylene-propylene-diene rubber (EPDM) waste. The EPDM recovered through this process showed mechanical properties similar to virgin rubber, making it suitable for applications like automotive weather strips and other related uses.

4.2.2. Solvent Based Recycling

Solvolysis uses solvents to break down polymers into smaller molecular structures. Hydrolysis and alcoholysis are two common solvolysis techniques used in the treatment of polyurethanes. In their study, Modesti et al.[62] explored glycolysis, a specific form of alcoholysis, to break down RRIM polyurethane into oligomers that can be reused to make new polyurethane materials. This method provides a more energy-efficient option than pyrolysis and shows significant potential for recovering valuable products. [63, 64]

4.2.3. Closed Loop Recycling

Palmer et al. research explores novel strategies for the recycling of glass fiber reinforced thermoset composites. The emphasis is on sheet moulding compounds (SMC) and dough moulding compounds (DMC) that are widely used in the automotive industry. This research, firstly, confronts the issue of mechanical properties degradation upon recycled material incorporation and, secondly, questions the cost, effectiveness of recycling processes. Thanks to the application of groundbreaking grinding techniques and a newly developed zigzag air classification method, the study succeeds in producing high, quality recycled material with a preserved fiber length. This is why it can be used as reinforcement and not just as a filler.

These results contradict the conventional understanding that recycling degrades composite materials. They provide a feasible solution to achieve recycling targets such as those set by the EU's End, of, Life Vehicle Directive. This is also a way to cut down on the consumption of new raw materials. The study underlines the possibilities of extensive and economically viable closed, loop recycling in the car and composites sectors. This is in line with the overall green transition[12, 21, 33].

4.3. Energy Recovery

4.3.1. Incineration

Incineration burns thermoset waste at temperatures over 1000ºC to recover energy, and can be considered as a thermal recycling method. It is a method that works well for mixed or contaminated waste streams and can be integrated into municipal solid waste management systems. Though, incineration is burdened by severe challenges, such as the release of various pollutants, including carbon dioxide (CO) and other toxic compounds. These discharges have caused the introduction of rules in some areas. Still, there is also the possibility of coprocessing thermoset waste in cement kilns. Thus, the organic material can be used as a fuel source, while the inorganic residues, such as fibers, are utilized as an addition to cement clinkers. However, it seems that the energy efficiency of the process can be lowered due to certain additives as well. For instance, flame retardants may absorb heat and calcium carbonate may break down during combustion, thus making incineration a less effective choice[32, 42, 65].

4.3.2. Fluidised bed combustion

Fluidized bed combustion is a different thermal method mainly used for the recovery of reinforcing fibers such as carbon or glass fibers. The University of Nottingham developed this technique where the polymer matrix is oxidized at about 500C in a silica sand fluidized bed. Then a secondary chamber at around 1000ºC ensures complete oxidation. The fibers are separated by gas streams and collected with cyclones. At the same time, fillers are returned to the process, and the energy released is used again. Nevertheless, the method's high temperatures and pressures may still affect the mechanical properties of the fibers. So shorter, lower quality fibers result. Additionally, the method's high, energy consumption and operating costs make it less scalable, thus difficult to be widely used[66, 67].

4.3.3. Pyrolysis

The process [68] involves pyrolysis, which thermally decomposes thermoset composites in an oxygen, free environment at temperatures of approximately 600ºC to 800ºC. The polymer matrix is broken down into low molecular weight liquids and gases, while inorganic fillers and fibers are preserved. The organic materials obtained can either be used as fuel or as chemical feedstock, and the fibers are allowed to keep their structural integrity. However, despite the existence of industrial, scale pyrolysis plants in operation, there are still challenges to be solved. Among these challenges are temperature optimization to prevent filler degradation, particularly in sheet molding compounds, and the removal of hazardous additives such as brominated flame retardants. Besides that, fiber sizing, for example, may be necessary as a post, treatment process to recover the fibers properties. On the other hand, microwave pyrolysis, a potential alternative method, could provide quicker and more uniform heating with lesser energy consumption. Nonetheless, it is still a laboratory, scale process due to problems such as char residue on fibers[69].

4.4. Radiation Techniques

Radiation technology opens up unique possibilities in the processes of recycling crosslinked polymers. On top of that, the introduction of ionizing radiation to a material can eventually lead to either crosslinking or the breaking (scission) of polymer chains, which makes the technology an instrument capable of handling recovery of materials and chemical recycling simultaneously.

4.4.1. Radiation Crosslinking

One of the main issues with recycled polymers is their reduced mechanical properties, which can be effectively mitigated through radiation crosslinking by reinforcing their network structure. For instance, the work of Zhang et al.[2, 74] demonstrated that the irradiation of ethylene vinyl acetate (EVA) and high, density polyethylene (HDPE) blends led to a considerable enhancement of elongation, flexibility, and heat aging resistance. Moreover, Spenadel et al.[18] identified that the irradiation of low, density polyethylene (LDPE) combined with elastomers resulted in improved corona resistance and flexibility. Thus, it can be considered as an appropriate material for the production of automotive fascia.

4.4.2. Radiation Induced Degradation

Radiation can improve the breakdown of polymers and support chemical recycling processes. For example, irradiating polypropylene (PP) in an oxidative environment can cause chain scission. This process reduces the energy needed for pyrolysis. Zhao et al [75] observed that the irradiation of PP facilitated pyrolysis at reduced temperatures, which may influence the nature of the decomposition products.

4.5. Radiation Assisted Devulcanization

Radiation can significantly enhance the breakdown of polymers, thus facilitating chemical recycling techniques. For instance, irradiation of polypropylene (PP) in an oxidative environment leads to chain scission. Such a process diminishes the energy required for pyrolysis. Zaharescu et al.[18] reported that gamma irradiation of rubber waste in the presence of oxygen effectively breaks CS bonds. This process results in successful devulcanization. This innovative method not only provides a viable alternative to conventional devulcanization methods but also has the potential to considerably enhance the properties of the material.

5. Advances in Recycling Technology

5.1. The Role of Catalysts in Chemical Recycling

Catalysts are essential to chemical recycling, which is also called feedstock recycling. The procedure is about depolymerization, i.e., cleaving polymers to monomers or other chemicals of interest. Their involvement can be summarized in the following way:

5.1.1. Thermal Cracking Utilizing Catalysts

The application of catalysts is a mainstay of thermal degradation processes. Higher reaction temperatures can be avoided, better yields are obtained, and formation of the desired product becomes more selective [70].

5.1.2. Catalytic Degradation to Aromatics

Researchers led by Uemichi et al. have designed zeolite, based catalytic systems to efficiently degrade polyolefins into valuable aromatic compounds. In this process, the catalysts used are HGallosilicate and HBorosilicate, which are capable of converting polyethylene (PE) and polypropylene (PP) into benzene, toluene, and xylenes (BTX). It is worth mentioning that the yields can be as high as 61.8% for BTX and 75.5% for C3, C5 olefins when the reaction is carried out at 525^{o}C. Moreover, chlorine, tolerant catalysts like HGalloaluminosilicate make it possible to convert low, density polyethylene (LDPE) into aromatic hydrocarbons even in a mixture with polyvinyl chloride (PVC), which is known to cause problems because of the release of chlorine[51].

5.1.3. Supercritical Fluids Combined with Catalysts

Supercritical fluids such as supercritical carbon dioxide and water are not necessarily used together with catalysts. However, they can substantially enhance the selective depolymerization process. For instance, catalysts are used in advanced systems to help the reaction proceed to the targeted monomers[71].

The employment of catalysts is advantageous in several aspects. The energy requirement can be less than that of pure pyrolysis. The selectivity and yield of the target monomers or oligomers can be improved. The issues of coking and the formation of side products can be reduced. The reaction process can be simplified as well.

5.2. Development of Recyclable Crosslinked Polymers

Recycling crosslinked polymers is a big challenge due to their three, dimensional network structure. This network makes it hard to melt or dissolve them. Recently, catalysts have been introduced that facilitate bond exchange reactions in a controlled environment. Thanks to this advancement, these polymers can be reprocessed without losing their mechanical strength.

5.2.1. Catalyst Enabled Covalent Adaptable Networks (CANs)

Covalent adaptable networks have dynamic covalent bonds that can rearrange themselves when exposed to certain conditions, typically involving heat or catalysts. They can be categorized as Associative (Examples include Transesterification and Olefin Metathesis) and Dissociative: Examples include Diels Alder reactions and urethane chemistry. [72]

5.2.2. Transesterification Reactions

They are utilized in vitrimers, which are networks that exhibit thermoplastic behavior when heated beyond a specific temperature threshold. The catalyst employed usually is Zinc (II) Acetylacetonate. It facilitates the transesterification process between esters and hydroxyl groups. [73]

5.2.3. Silyl Ether Exchange

This process involves reversible reactions. The catalysts typically employed are Acids or bases (organocatalyst activated excluding metals). This method helps create dynamic siloxane networks. It promotes sustainable recycling by removing heavy metals. [74]

5.2.4. Olefin Metathesis (Ring Opening Metathesis Polymerization – ROMP)

This technique makes use of dynamic double bonds that can either be recross linked or degraded. Catalyst in this case is Grubbs' Catalyst (Ruthenium based).[71] It assists the depolymerization process, making it highly suitable for closed loop recycling. [70]

5.3. The Function of Additives and Compatibilizers

Additives such as stabilizers, plasticizers, fillers, processing aids, and UV absorbers can partially restore the properties lost during polymer degradation and reprocessing. [72] Compatibilizers improve interfacial adhesion between otherwise incompatible polymers, thereby reducing phase separation and brittleness. Reactive compatibilization, including the use of maleic-anhydride-grafted polyolefins, can form interfacial copolymers and improve the mechanical performance of recycled blends. However, these approaches are more relevant to mixed polymer streams and should be applied according to the composition and intended use of the recycled material. [21, 72, 75]

5.3.1. Reactive Compatibilization

The process involves a chemical reaction during blending that forms copolymers at the interface. This technique is significantly more effective than merely adding premade compatibilizers. As a case in point, Ali et al. (2002) demonstrated that in polypropylene (PP) and polyamide (PA) blends, the extrusion of grafted maleic anhydride (MAH) PP leads to better adhesion to the PA phase. The use of reactive compatibilization is a key element in the closed, loop recycling of mixed postconsumer waste[6, 75, 76].

6. Applications of Recycled Materials in the Automotive Industry

The automotive sector turns to recycled materials more and more to improve sustainability, reduce costs, and comply with environmental regulations. Recycled rubber, composites, and thermosets are the main materials that support secondary applications, interior parts, and lightweighting strategies. The following provides an in-depth analysis of their usage[14, 15, 41].

6.1. Key Applications in the Automotive Industry

They are used in rethreaded tires which are used in commercial vehicles like trucks and buses, these products can cut raw material use by up to 70%. They can be used as Crumb Rubber Modifiers (CRM) in Asphalt which improve road durability while also reducing tire noise inside vehicle cabins.[13]. Rubber obtained from damping components can be recycled into Acoustic Insulation Mats and anti-vibration mounts which are used in engine mounts, suspension bushings and exhaust hangers.[77]

Rubber obtained from seals and gaskets are typically repurposed into door seals, window seals, and weatherstripping use a mix of recycled rubber and new material. This combination helps maintain flexibility and resist weather conditions.[21, 78, 79]

6.2. Recycled Composites in Vehicle Interiors

The main areas using recycled are fiber reinforced plastics, thermoplastic composites, natural fiber composites.[80–82] It is commonly used in dashboard, instrument panels, [38, 43, 83] parts of the door panels or trim, [84] seats and the cushions. [85] It is also used in the headliners and carpets used in cars. [86]

6.3. Advantages and disadvantages of using Recycled Composites in Interiors

Advantages include weight reduction, lower CO_2 footprint, cost reduction and flexibility during design. Challenges associated with traditional thermosets are that they are non-recyclable and usually end up in the landfills, so recycling them like this is helping the environment too.

7. Conclusion

Recycling crosslinked polymers from automotive waste remains challenging because permanent crosslinks, contamination, material heterogeneity, and degradation limit the effectiveness of conventional processing. Mechanical recycling and devulcanization offer relatively simple routes for producing fillers and secondary rubber products, whereas chemical methods such as solvolysis and pyrolysis can recover oligomers, chemical feedstocks, and reinforcing fibers. Radiation-assisted processing and recyclable networks such as vitrimers provide promising alternatives, although their energy requirements, cost, safety, and scalability require further evaluation.

Future development should combine design-for-recycling principles with improved sorting, selective bond cleavage, life-cycle assessment, and closed-loop collaboration between automotive manufacturers and recyclers. The most sustainable approach will be the one that balances material recovery, product performance, environmental impact, and economic feasibility.

Compliance with ethical standards

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