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Environmental Justice at the Bioenergy-Biomass-Agroforestry Nexus: A Contemporary Integrative Review of Ecosystem Trade-Offs, Governance, And Circular Bioeconomy Pathways

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ABSTRACT: Bioenergy, biomass valorization, and agroforestry are increasingly promoted as linked pathways for decarbonization, rural development, climate adaptation, and circular bioeconomy transitions. However, these pathways may also redistribute environmental burdens, intensify competition over land and biomass, or marginalize communities when ecological limits and justice principles are treated as secondary concerns. This integrative review synthesizes literature on bioenergy, biomass supply chains, agroforestry, life-cycle and techno-economic assessment, participatory governance, and environmental justice. The review argues that the most defensible transition pathway is not generalized biomass expansion, but context-specific, multifunctional systems that combine agroforestry, sustainable residue use, appropriate conversion technologies, spatial planning, procedural safeguards, and benefit-sharing mechanisms. The synthesis develops a justice-centered assessment framework based on ecological suitability, feedstock legitimacy, technological proportionality, justice performance, and adaptive governance. The article concludes that biomass-based transitions are credible only when they are renewable, restorative, inclusive, and accountable.

KEYWORDS: environmental justice; bioenergy transition; biomass valorization; agroforestry systems; circular bioeconomy; water-energy-food nexus; participatory governance

1. INTRODUCTION

The decarbonization of energy systems has renewed interest in biomass, bioenergy crops, and agroforestry-based production systems. Biomass is materially versatile because it can be converted into heat, electricity, biofuels, biochar, syngas, and other bioproducts. Agroforestry also offers the possibility of combining biomass production with soil protection, microclimate regulation, biodiversity conservation, carbon storage, food production, and livelihood diversification. Yet these outcomes should be understood as possibilities rather than automatic consequences. Bioenergy and agroforestry can generate ecological and social benefits, but they can also create trade-offs involving land-use change, water demand, biodiversity loss, soil degradation, supply-chain pressure, unequal benefit distribution, and localized health burdens (Berndes et al., 2015; Chowdhury et al., 2025; Winberg et al., 2023).

This review positions environmental justice as the organizing principle for evaluating the bioenergy-biomass-agroforestry nexus. Environmental justice is used here in four related senses. Distributive justice concerns how benefits and burdens are allocated. Procedural justice concerns whether affected groups participate meaningfully in decisions. Recognition justice concerns whether local knowledge, tenure arrangements, cultural values, and historical marginalization are acknowledged. Restorative justice concerns whether interventions repair degraded landscapes and inequitable resource systems rather than creating new burdens. These dimensions are essential because a biomass facility can be technically feasible yet socially contested, an agroforestry project can store carbon yet fail under insecure tenure, and a bioenergy supply chain can reduce fossil fuel use while transferring ecological pressure to rural or peri-urban communities (Govindarajan & Ganesh, 2022; Rettenmaier & Hienz, 2014; van Dam et al., 2009).

The central argument of this review is conditional. Biomass-based transitions are most likely to support environmental justice when they are embedded in multifunctional landscapes, governed through meaningful participation, assessed with life-cycle and techno-economic evidence, and evaluated against locally relevant food, water, land, health, and livelihood outcomes. This position avoids two weak extremes. The first is technological optimism, which assumes that advanced conversion technologies or circular bioeconomy language can resolve ecological and social conflicts. The second is blanket skepticism, which rejects biomass-based pathways despite evidence that agroforestry, residues, biochar, and well-governed local conversion systems can contribute to climate resilience and rural development (Blair et al., 2021; Castle et al., 2022; Coe et al., 2014).

The novelty of this review is threefold. First, it integrates environmental justice with technical biomass debates, rather than treating justice as an additional policy concern after technological feasibility has already been assumed. Second, it reframes agroforestry as a justice-relevant biomass strategy because tree-based systems can generate residues and ecosystem services while maintaining food, soil, water, and livelihood functions. Third, it proposes a justice-centered assessment framework that links ecological suitability, feedstock legitimacy, technological proportionality, justice performance, and adaptive governance. This framework moves the review beyond description by showing how sustainability claims can be evaluated across ecological, technological, economic, and governance dimensions.

2. REVIEW APPROACH, SCOPE, AND CITATION INTEGRITY

This article uses a narrative-integrative review approach rather than a meta-analysis. The approach is appropriate because the literature covers heterogeneous systems, methods, geographies, and outcomes, including life-cycle assessment, techno-economic analysis, policy review, systematic mapping, participatory mapping, case study research, modelling, and conceptual scholarship. A pooled quantitative estimate would risk false comparability because a life-cycle assessment of pyrolysis, a participatory study of agroforestry adoption, and a policy review of bioenergy governance do not measure the same outcome or operate at the same scale (Foong et al., 2024; Sardeshpande et al., 2025; Tapia et al., 2019).

The review synthesizes evidence across five domains: environmental trade-offs in bioenergy and biomass production; agroforestry as a multifunctional biomass and livelihood strategy; techno-economic and life-cycle limits of circular bioeconomy pathways; biomass supply chains, land competition, and participation; and governance, policy integration, and environmental justice. This structure was selected to reduce repetition and to shift the article from a descriptive list of studies toward a deeper synthesis of mechanisms, trade-offs, and decision criteria.

Citation integrity was strengthened in this revised version by removing empty placeholder citations, retaining only traceable in-text citations, and aligning the reference list with the sources actually cited in the manuscript. General statements are supported by references that match the claim type. For example, claims about land-use change are supported by bioenergy land-use literature, claims about agroforestry ecosystem services are supported by agroforestry reviews or systematic maps, and claims about technology performance are supported by life-cycle or techno-economic studies. The reference list includes only sources cited in the text and tables.

3. THEMATIC SYNTHESIS

3.1 Environmental trade-offs in bioenergy and biomass production

Bioenergy is frequently justified through climate mitigation, but the literature shows that greenhouse-gas accounting is only one part of a wider sustainability question. Net outcomes depend on land-use change, crop choice, conversion efficiency, co-product use, residue removal intensity, transport distance, soil carbon response, and supply-chain organization. When perennial or diversified systems replace highly intensive annual systems, bioenergy crops may support biodiversity and ecosystem-service gains. However, when dedicated energy crops replace forests, wetlands, species-rich grasslands, or food-producing landscapes, carbon and biodiversity losses can undermine expected climate benefits (Berndes et al., 2015; Davis et al., 2011; Winberg et al., 2023).

Land-use change is therefore a central justice issue. It is not merely a technical parameter in carbon accounting because it affects access to land, food security, cultural landscapes, and common resources. Communities with weaker tenure security or limited political influence may be more exposed to displacement, restricted access, or livelihood uncertainty. For this reason, sustainability criteria must include land rights, food security, and governance, not only emissions reduction (van Dam et al., 2009; Rettenmaier & Hienz, 2014).

Soil carbon and soil health provide more promising but still conditional pathways. Perennial vegetation, tree-based systems, organic amendments, and reduced disturbance may improve soil functions, yet residue removal can reduce soil cover, nutrient cycling, and organic matter inputs if extraction exceeds ecological thresholds. A justice-oriented biomass strategy should treat soil not simply as a feedstock platform but as shared ecological infrastructure that supports long-term productivity, water regulation, and community resilience (Perry et al., 2023; Yadav et al., 2023).

Water and health impacts also require explicit attention. Bioenergy crops may increase water demand or alter local hydrology depending on species, irrigation, fertilization, and climate. Biomass conversion can generate air pollutants, odours, wastewater, ash, and occupational risks when siting and emissions control are weak. These concerns become environmental justice issues when facilities are placed near communities with limited capacity to negotiate safeguards or compensation (Chowdhury et al., 2025; Elagib & Al-Saidi, 2020).

Table 1. Analytical matrix of sustainability dimensions, trade-offs, and justice questions

Dimension	Mechanism	Potential benefit	Main trade-off	Justice question	Key sources
Land-use change	Dedicated crops, marginal-land claims, residue mobilization	Potential fossil substitution and rural value creation	Food-energy competition, indirect land pressure, tenure conflict	Whose land use is displaced or restricted?	Berndes et al., 2015; Davis et al., 2011; van Dam et al., 2009

Dimension	Mechanism	Potential benefit	Main trade-off	Justice question	Key sources
Soil carbon and fertility	Perennial roots, litter inputs, reduced disturbance, biochar	Improved soil organic carbon, nutrient cycling, and soil structure	Residue removal may reduce cover and soil inputs	Are soil functions protected as shared ecological infrastructure?	Perry et al., 2023; Yadav et al., 2023; Vuppaladadiyam et al., 2023
Biodiversity	Perennial crops, polycultures, agroforestry structure	Habitat complexity and landscape heterogeneity	Monoculture plantations or habitat conversion	Whose ecosystem services are protected or lost?	Castle et al., 2022; Winberg et al., 2023
Water and health	Irrigation, processing, facility siting, emissions control	Water buffering and cleaner energy under strong safeguards	Water stress, pollution exposure, occupational risks	Who bears exposure and who receives benefits?	Chowdhury et al., 2025; Elagib & Al-Saidi, 2020
Participation and governance	Consultation, co-design, living labs, platforms	Legitimacy, learning, conflict reduction	Tokenistic participation and power asymmetry	Do affected communities shape decisions?	ElDidi et al., 2026; Govindarajan & Ganesh, 2022; Rastorgueva et al., 2026

3.2 Agroforestry as a justice-relevant biomass strategy

Agroforestry is one of the most promising pathways because it embeds biomass production within multifunctional landscapes. Tree-based systems can generate residues for energy while supporting soil cover, carbon storage, biodiversity, microclimate regulation, food production, and income diversification. Compared with biomass strategies that treat land mainly as a feedstock source, agroforestry can link energy transitions with rural livelihoods and ecosystem services (Barman et al., 2024; Castle et al., 2022; Muthuri et al., 2023).

The justice value of agroforestry lies partly in its distributive potential. Smallholders may benefit from fruit, fodder, fuelwood, timber, shade, improved soil fertility, and diversified income. Homestead, peri-urban, and market-oriented agroforestry systems can support household food security and local resilience when supported by tenure security, extension, finance, and market access (Ararsa et al., 2025; Pandit et al., 2019; van Noordwijk, 2021).

Nevertheless, agroforestry should not be romanticized as automatically inclusive. Adoption barriers include delayed returns, insecure tenure, high initial investment, insufficient technical knowledge, weak extension services, uncertain markets, and fragmented policy support. These barriers are justice issues because they determine who can participate and who is excluded from the benefits of transition (Areal et al., 2026; Simelton et al., 2017; Tranchina, Reubens, et al., 2024).

Recognition justice is also important. Participatory mapping and local ecological knowledge can reveal agroforestry opportunities and constraints that external planners may miss. Local preferences for species, customary land uses, water access, cultural values, and gendered labour arrangements should shape design decisions. Without such recognition, agroforestry programmes may impose technically plausible but socially inappropriate systems (Sardeshpande et al., 2025; van Noordwijk, 2021).

Table 2. Agroforestry pathways for just biomass transitions

Pathway	Biomass role	Ecosystem/livelihood value	Adoption constraint	Policy or research response	Key sources
Residue-based farm energy	Prunings, branches, and crop-tree residues	Local energy, biochar, reduced waste	Unclear sustainable removal thresholds and competing household uses	Set residue thresholds and protect soil and household functions	Nithes et al., 2025; Tapia et al., 2019
Homestead agroforestry	Small-scale woody and agricultural biomass	Food security, shade, income diversity, household resilience	Limited capital, extension, and market access	Support local nurseries, finance, extension, and value chains	Ararsa et al., 2025; Muthuri et al., 2023
Market-oriented agroforestry	Tree products and residues within commercial farming	Farm income, food security, carbon and ecosystem services	Market volatility and unequal access to inputs	Design market links with safeguards for smallholders	Pandit et al., 2019; Kodithuwakku et al., 2025
Peri-urban agroforestry	Urban and peri-urban woody	Food access, degraded-land	Land-use pressure, tenure	Integrate land-use planning, water	Ayambire et al., 2019; Lal et al., 2021

Pathway	Biomass role	Ecosystem/livelihood value	Adoption constraint	Policy or research response	Key sources
	biomass and residues	rehabilitation, heat reduction	uncertainty, public health risks	safety, and tenure protections	
Indigenous/local agroforestry	Locally valued species and spatial knowledge	Recognition of cultural values and locally appropriate restoration	External design may overlook customary rights	Use participatory mapping and co-design	Sardeshpande et al., 2025; van Noordwijk, 2021

3.3 Techno-economic feasibility and circular bioeconomy limits

Conversion technology is necessary but not sufficient for just biomass transitions. Gasification, pyrolysis, co-pyrolysis, biohydrogen, biochar, co-firing, and microwave-assisted processes can produce useful energy carriers and materials, but their feasibility depends on capital cost, feedstock quality, conversion efficiency, scale, emissions control, logistics, co-product markets, and policy incentives (Guerrero et al., 2023; Im-orb et al., 2018; Kamaruzaman et al., 2023).

Life-cycle assessment and techno-economic analysis are essential because they reveal whether a technology reduces impacts across the full system or merely shifts burdens outside the project boundary. Microwave-assisted pyrolysis, for example, may offer process advantages, but its sustainability depends on equipment costs, energy input, scale-up feasibility, feedstock collection, co-product use, and emissions performance. Similar caution applies to biohydrogen, biochar, and integrated gasification pathways (Foong et al., 2024; Kichonge et al., 2026; Vuppaladadiyam et al., 2023).

Circular bioeconomy framing is useful when it reduces waste, improves resource efficiency, and returns value to local systems. However, biomass residues are not necessarily waste. They may already support soil fertility, livestock bedding, household energy, composting, informal livelihoods, or cultural practices. A residue should be considered available for energy only after its ecological and social functions have been assessed (Lewandowski, 2015; Nithes et al., 2025; Tapia et al., 2019).

3.4 Biomass supply chains, land competition, and participation

Supply chains are where many sustainability claims become either credible or fragile. Biomass must be produced, collected, stored, transported, pretreated, converted, and distributed. Each step creates costs, emissions, labour requirements, and governance questions. A project may appear feasible at the plant gate while relying on unrealistic assumptions about residue availability, farmer participation, moisture content, transport distance, or seasonal supply (Blair et al., 2021; Lewandowski, 2015; Rauch, 2017).

Food-energy competition remains a core concern. Agroforestry residues and marginal-land strategies can reduce competition, but they do not remove it. Residues may be needed for soil cover, livestock, compost, or household energy. Land described as marginal may be ecologically important or socially used. Justice-oriented planning must therefore ask not only whether biomass exists, but who currently depends on it and what functions would be displaced (Davis et al., 2011; Tapia et al., 2019).

Participation is frequently recommended, but it must be meaningful rather than symbolic. Multi-stakeholder platforms, living labs, participatory mapping, and regional platforms can improve legitimacy and learning when they influence problem definition, siting, feedstock strategy, mitigation, monitoring, and benefit sharing. Participation becomes weak when communities are invited only after the main decisions have been made (ElDidi et al., 2026; Govindarajan & Ganesh, 2022; Rastorgueva et al., 2026).

Table 3. Biomass conversion pathways and justice-sensitive assessment priorities

Pathway	Typical feedstock	Key promise	Key constraint	Justice-sensitive assessment priority	Key sources
Gasification	Agricultural residues, woody biomass, industrial biomass	Heat, power, and syngas for decarbonization	Capital cost, tar removal, feedstock consistency	Evaluate local supply-chain risk, emissions control, and benefit sharing	Guerrero et al., 2023; Kamaruzaman et al., 2023
Pyrolysis and co-pyrolysis	Lignocellulosic residues and wastes	Bio-oil, biochar, and biohydrogen potential	Co-product markets, scale, and process optimization	Combine TEA, LCA, and soil-use value of biochar	Im-orb et al., 2018; Vuppaladadiyam et al., 2023
Microwave-assisted pyrolysis	Biomass and selected waste streams	Potential process control and efficiency gains	Equipment cost and scale-up uncertainty	Use full-boundary LCA and compare with conventional pathways	Foong et al., 2024; Li et al., 2024
Biohydrogen	Lignocellulosic biomass via co-pyrolysis or gasification	Renewable hydrogen and higher-value energy carrier	Commercial readiness and integrated system cost	Distinguish laboratory, modelled, pilot,	Kichonge et al., 2026

Pathway	Typical feedstock	Key promise	Key constraint	Justice-sensitive assessment priority	Key sources
				and commercial evidence	
Biochar	Crop residues, manure, sludge, woody biomass	Soil amendment, carbon storage, nutrient recycling	Quality standards, contamination, market access	Assess safe application and local farmer access	Trollip & Merckel, 2025; Vuppaladadiyam et al., 2023

4. JUSTICE-CENTERED ASSESSMENT FRAMEWORK

The synthesis supports a five-part framework for evaluating bioenergy-biomass-agroforestry interventions. The framework is designed to prevent generic claims and to guide evidence-based screening of projects, policies, and research proposals.

First, ecological suitability asks whether the proposed system protects or improves biodiversity, soil carbon, water resources, and landscape integrity. This criterion prevents mitigation claims from being accepted when they rely on damaging land conversion or excessive biomass extraction. Second, feedstock legitimacy asks whether biomass is genuinely available after accounting for food, feed, fibre, fuel, soil, cultural, and livelihood functions. This criterion is essential because residue availability is often overestimated when existing uses are ignored. Third, technological proportionality asks whether the conversion technology is appropriate for local feedstock scale, skills, financing, emissions controls, logistics, and markets. Fourth, justice performance asks whether benefits, burdens, participation, recognition, and risk are fairly distributed. Fifth, adaptive governance asks whether monitoring, learning, grievance mechanisms, and institutional coordination can respond to unexpected outcomes.

Table 4. Justice-centered assessment framework for biomass-based transitions

Framework component	Core question	Evidence needed	Failure mode if ignored	Application
Ecological suitability	Does the system protect biodiversity, soil, water, and landscape integrity?	Baseline ecology, land-use history, water demand, biodiversity value, soil carbon	Carbon gains are overstated while ecological losses are displaced	Project screening and land-use planning
Feedstock legitimacy	Is biomass available after existing ecological and social uses are protected?	Residue budgets, household-use mapping, livestock needs, soil cover requirements	Circularity claims extract resources needed by soils and communities	Residue policy, contracts, and supply-chain design
Technological proportionality	Is the technology appropriate to feedstock scale, skills, cost, and safeguards?	TEA, LCA, emissions control, local capacity, co-product markets	Technically impressive systems fail or externalize costs	Technology selection and investment appraisal
Justice performance	Are benefits, burdens, participation, recognition, and risks fairly distributed?	Benefit-sharing analysis, participation records, tenure review, exposure assessment	Projects become contested despite technical feasibility	Environmental and social safeguards
Adaptive governance	Can the system learn and respond over time?	Monitoring plan, grievance mechanism, institutional roles, data access	Delayed impacts remain invisible and unmanaged	Implementation, monitoring, and policy revision

This framework distinguishes four transition pathways. Extractive bioenergy expands feedstock demand faster than safeguards and is therefore high risk. Technocratic circularity optimizes conversion technology but under-recognizes social uses of biomass. Multifunctional agroforestry treats biomass as one product within a broader landscape strategy and is more promising when tenure and markets are supportive. Justice-centered circular agroforestry embeds residues and conversion technologies within participatory governance, life-cycle assessment, benefit sharing, and adaptive monitoring. The fourth pathway is the most consistent with the evidence synthesized in this review.

5. RESEARCH GAPS AND FUTURE AGENDA

First, future research should prioritize longitudinal evidence. Tree systems, soil carbon, markets, farmer trust, and institutional performance evolve over years or decades. Short project cycles may capture adoption intentions or early biomass yields while missing delayed burdens, land-value shifts, gendered labour changes, or institutional fatigue (Muthuri et al., 2023; Perry et al., 2023).

Second, integrated assessment should combine life-cycle assessment, techno-economic analysis, spatial modelling, and justice metrics. Current studies often excel in one domain while treating others superficially. A next-generation assessment should include environmental indicators, financial viability, supply-chain risk, distribution of benefits, procedural quality, recognition of local knowledge, and exposure to pollution or land pressure (Cusva-García et al., 2026; Foong et al., 2024; Guerrero et al., 2023; Govindarajan & Ganesh, 2022).

Third, urban and peri-urban agroforestry require deeper study. These systems sit at the intersection of food security, land speculation, waste management, water reuse, and urban environmental justice. They may provide biomass and ecosystem benefits, but they also require governance to address contamination, tenure, access, and public health (Ayambire et al., 2019; Haldar et al., 2021; Lal et al., 2021).

Fourth, research should develop clearer thresholds for sustainable residue removal and agroforestry biomass use. The term residue can obscure ecological value. Studies should specify how much biomass can be removed under different soils, climates, slopes, farming systems, and livelihood contexts without undermining soil organic matter, nutrient cycling, erosion control, household energy, or livestock systems (Nithes et al., 2025; Tapia et al., 2019).

Fifth, more attention is needed to benefit-sharing and ownership models. Community bioenergy, cooperatives, farmer-owned processing, municipal agroforestry partnerships, and local biochar use may distribute benefits differently from investor-owned facilities. Comparative research should examine which models best support procedural justice, local value retention, and ecological safeguards (Woods et al., 2006; Govindarajan & Ganesh, 2022).

Table 5. Research gaps and publication-ready agenda

Gap	Why it matters	Current limitation	Suggested method	Expected contribution
Long-term justice outcomes	Tree systems, soil carbon, and trust change slowly	Short projects miss delayed benefits and burdens	Longitudinal mixed-method studies	Evidence on durability and distribution of outcomes
Integrated LCA-TEA-justice metrics	Technical viability can hide social and ecological costs	Assessments often isolate emissions, cost, or policy	Coupled LCA, TEA, spatial justice mapping, and interviews	Credible project screening and policy design
Urban and peri-urban agroforestry	Cities create land, water, and food-security tensions	Evidence is limited and governance fragmented	Comparative case studies and participatory planning	Safer water reuse and inclusive urban land strategies
Residue availability thresholds	Residues have soil, livestock, and household functions	Available biomass is often assumed too easily	Field trials, nutrient budgets, and social-use mapping	Avoids extraction that degrades soils or livelihoods
Governance quality	Participation can be transformative or symbolic	Many studies report platforms without evaluating power	Process tracing and equity-sensitive evaluation	Clearer evidence on meaningful participation

6. LIMITATIONS AND BOUNDARY CONDITIONS

This review is positioned as a conceptual and integrative synthesis rather than a systematic review or meta-analysis. Its main contribution is not a new dataset, but a revised interpretation of the existing evidence base through an environmental justice lens. Because the literature includes different methods, regions, technologies, and scales, findings should not be interpreted as directly comparable across all contexts.

The framework proposed here is intended to support evaluation, not to replace deliberation. Ecological suitability, feedstock legitimacy, technological proportionality, justice performance, and adaptive governance can help researchers and policymakers ask better questions. They cannot determine what a community should accept or reject. Decisions about land, trees, biomass, and energy involve values that cannot be reduced to net present value or carbon dioxide equivalents.

Agroforestry should be presented as a promising platform rather than a guaranteed solution. Its strengths are substantial, but adoption barriers such as insecure tenure, delayed returns, limited finance, weak technical support, and fragmented institutions can prevent benefits from reaching the groups most often invoked in sustainability narratives. Similarly, this review should not be read as a universal endorsement of bioenergy expansion. Biomass pathways are most credible when they avoid high-carbon land conversion, protect soil and water functions, respect existing biomass uses, and deliver tangible local benefits.

7. CONCLUSION

The reviewed literature supports a clear but cautious conclusion: bioenergy, biomass valorization, and agroforestry can contribute to decarbonization, rural development, and landscape restoration, but only under conditions that respect ecological limits and environmental justice. The most promising systems are not those that maximize biomass extraction, but those that embed biomass within multifunctional landscapes, especially agroforestry systems that also support soil, water, biodiversity, food security, and livelihoods.

Technology matters, but it does not substitute for governance. Conversion pathways such as gasification, pyrolysis, microwave-assisted processes, biohydrogen, and biochar require life-cycle and techno-economic assessment, emissions control, market realism, and community safeguards. Supply-chain design must also account for existing biomass uses, land tenure, food security, residue thresholds, logistics, and benefit sharing.

The strongest contribution of this review is the justice-centered assessment framework based on ecological suitability, feedstock legitimacy, technological proportionality, justice performance, and adaptive governance. This framework clarifies why bioenergy, biomass, and agroforestry should be read together rather than in disciplinary isolation. A biomass-based transition is most credible when it is not only renewable, but also restorative, inclusive, and accountable.

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