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Research Article

Optimising Transportation Systems for Sustainable Agricultural Supply Chains: Integration of Smart Logistics and Precision Farming Techniques

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Abstract

Integrating smart logistics and precision farming techniques transforms agricultural supply chains, addressing critical socio-environmental challenges such as resource overuse and inefficiencies. This paper explores how applying technologies like the Internet of Things (IoT), Big Data analytics, and Artificial Intelligence (AI) can enhance agricultural operations by optimising transportation, storage, and distribution processes. Smart logistics improve supply chain efficiency, reduce waste, and minimise carbon emissions, while precision farming focuses on data-driven decision-making to optimise input usage and enhance crop productivity. Case studies from Finland, Slovakia, and the Czech Republic demonstrate the potential of these integrated systems to deliver substantial economic, environmental, and operational benefits. However, the implementation of such technologies faces significant challenges, including high initial costs, data protection issues, and insufficient infrastructure. The paper concludes by highlighting the need for coordinated policy frameworks and continuous innovation to ensure the scalability and success of these technologies in diverse agricultural contexts.

Keywords: Smart Logistics; Precision Farming; Supply Chain Efficiency; Internet of Things (IoT); Sustainable Agriculture; Data-Driven Agriculture

Introduction

World agricultural systems face several socio-environmental challenges. The most salient and pressing among these challenges is the efficient and wise utilisation of water, land, and energy resources (Zhan et al., 2022). In order to overcome these hurdles, it is paramount that innovative and sustainable approaches are adopted and implemented. In agriculture, the growing stress and strain resulting from the rampant and excessive exploitation of natural resources have given rise to serious concerns and apprehensions regarding the long-term sustainability of production processes and their overall supply chains (Ding et al., 2021). Therefore, it is of utmost importance that proactive measures are taken to ensure the viability and resilience of our agricultural systems. One prominent area that requires immediate attention is the integration of state-of-the-art smart logistics concepts and technologies into the existing food supply chains (Chung, 2021). Smart logistics can be vital in optimising and streamlining agricultural product transportation, storage, and distribution. By employing advanced technologies, such as the Internet of Things (IoT), big data analytics, and artificial intelligence, optimised solutions can be devised to minimise waste, reduce carbon emissions, and maximise the overall efficiency of the supply chain (Pavlenko et al., 2020). Furthermore, precision agriculture techniques must be embraced and implemented to augment the sustainability of agriculture. Precision agriculture entails the utilisation of modern technologies, such as remote sensing, geographic information systems (GIS), and global positioning systems (GPS), to enhance the precision and accuracy of farming practices.

By integrating data-driven decision-making and precision farming techniques, farmers can optimise the use of resources and inputs, minimise unnecessary waste, and boost overall crop productivity (Zhan et al., 2022). The text is thoughtfully divided into six sections to explore and delve into these significant aspects comprehensively. These sections aim to analyse the various challenges faced by world agricultural systems thoroughly, highlight the urgency of finding innovative and sustainable solutions, emphasise the significance of incorporating smart logistics concepts, shed light on the importance of precision agriculture techniques, and outline the potential benefits and impacts associated with these advancements. By delving into each section, the reader will understand the socio-environmental challenges encountered by agricultural systems worldwide and the possible solutions and measures that can be adopted to address them (Ding et al., 2021). The text strives to provide an informative and enlightening narrative that encourages and fosters further research, collaboration, and implementation of sustainable agriculture practices. At the outset, there is a growing need for environmentally sustainable agricultural practices. The growing importance of agriculture and the increasing push for food production in developing countries is highlighted (Chung, 2021).

A case in point of logistics operations that increased efficiency in food production while closely working with farmers in Vietnam is presented. Further, exploring the logistics process associated with the transportation of chickens in Vietnam, it is emphasised that integrating logistics and smart farming can lead to innovation in agriculture (Pavlenko et al., 2020). The existing supply chain systems are fraught with the cost of production, product logistics, and increasing complexities. These challenges are, in turn, influenced by environmental costs such as wastewater management, waste disposal, and fuel costs. There is a necessity for developing innovative frameworks and tools to reduce environmental costs (Zhan et al., 2022). Thus, this work and series of research offer a potentially powerful multi-disciplinary approach that harnesses advances in logistics, transportation management, and vehicle routing optimisation disciplines to shape some of the technological dimensions of the optimisation problem consistent with technological advancements (Ding et al., 2021). The aggregated collection of problems can address several aspects of the food transportation lifecycle.

Background and Rationale

In a global market of interconnected economic and environmental systems, agricultural supply chains have constantly been focused on improving performance to respond to the nutritional needs of the growing world population (Negri et al., 2021). Traditional logistical systems focus on economy, resilience, and agility, often at the expense of social and environmental goals (Lin et al., 2023). The inadequacies of contemporary food supply chains extend beyond the basic demands for food safety and security; they constrain national economies in resource allocation and compromise environmental and social sustainability (Ivanov, 2022). A systemic transition to a smart logistics system is in progress. It promises to deliver what customers increasingly require: the right products at the right place and time, aligned with their destination (Negri et al., 2021). Today, more than ever, digital technologies are reshaping traditional production, storage, and logistics systems into more agile, efficient, and flexible processes (Ivanov, 2022). Technology is also transforming agriculture, where the economics of individual farms are built on each growing season due to long-term investments, making farmers highly risk-averse and resistant to change (Lin et al., 2023). Most logistical processes in agricultural supply chains contribute to necessary waste due to imperfect, missing, or misleading information. These inefficiencies result in extended delivery times, higher operational costs, delays, and supply shortages (Negri et al., 2021). Therefore, a paradigm shift toward sustainable logistics is essential. The lack of promotion of modern solutions among stakeholders and decision-makers further emphasises the need to investigate the role of smart logistics in enhancing system resilience (Ivanov, 2022).

Research Objectives

Agriculture is a critical component of the global economy, particularly in developing nations, where transportation systems are vital in managing supply chains (Gray, 2020). Over time, the persistent growth of societies has led to an increasing demand for processed food and agricultural products. Logistics significantly mitigate the imbalance between supply and demand (Borah et al., 2020). The global food supply chain is now transitioning from a time-based perspective to an emission-based focus, driven by the need for comprehensive sustainability (Yadav et al., 2022). In this context, smart logistics emerges as a strategy that efficiently manages information, waste, energy, and other resources within modern logistics systems. Additionally, precision agriculture, which focuses on using advanced technologies like GPS, remote sensing, and data analytics to enhance agricultural productivity while ensuring environmental sustainability, is gaining attention. However, integrating intelligent logistics and precision agriculture remains underexplored in academic research despite the potential for collaborative and sustainable outcomes (De & Singh, 2021). This research seeks to address this gap by analysing the relationship between smart logistics and precision farming, focusing on their combined impact on sustainable agriculture (Borah et al., 2020). It also aims to propose performance criteria and frameworks for improving outcomes, especially in third-party logistics operations in developing countries (Gray, 2020). Through these findings, the research will enhance the affordability and ecological balance of agricultural supply chains, thereby supporting sustainable development goals (Yadav et al., 2022).

Smart Logistics in Agricultural Supply Chains

The attached figure illustrates a highly integrated **smart farming system**, showcasing the essential role of **smart logistics** in creating efficient, sustainable agricultural supply chains. Automation**, digitalisation,** and **real-time data utilisation** have significantly transformed agricultural operations by enhancing performance and productivity. For instance, **Internet of Things (IoT)** devices monitor crop health, control irrigation, and manage environmental conditions. At the same time, **Geographic Information Systems (GIS)** and **Artificial Intelligence (AI)** facilitate optimal resource allocation, such as seed and nutrient distribution or monitoring livestock movements (Yadav et al., 2022; Remondino & Zanin, 2022). In the image, **drones** and **autonomous vehicles** can manage various tasks like aerial spraying, field mapping, and robotic harvesting, showcasing the potential of unmanned systems in precision agriculture. These technologies enable real-time decision-making and **logistics optimisation**, improving the timely delivery of agricultural products while minimising waste and reducing operational costs (Panetto et al., 2020). Integrating advanced **sensors** and **data processing systems** ensures that operations can adjust swiftly to changing field conditions, further enhancing efficiency across the supply chain. Moreover, the figure highlights the future of agricultural logistics, where autonomous systems will play a significant role in reshaping supply chains by improving **task precision** and reducing human labour dependency. This shift is expected to revolutionise how agricultural goods are produced, processed, and delivered, making the entire value chain more resilient and responsive to market demands (Remondino & Zanin, 2022; Alesiuniene et al., 2021).

Figure 1: Integrating Precision Farming, Automation, and Smart Logistics for Sustainable Food Production *(**Source:** rainyweathers.com)*

Concepts and Technologies

Smart logistics in agriculture involve using advanced technologies and data analytics to streamline and optimise transportation, distribution, and delivery processes (Chung, 2021). Transportation and logistics are critical activities within agricultural production, yet inefficiencies, particularly in developing nations like India, lead to substantial waste. For instance, around 21.5% of all fruits and vegetables produced—equating to 574 million tonnes—are wasted due to inadequate post-harvest management, poor infrastructure, and lack of cold chain facilities (Ding et al., 2021). This demonstrates the importance of integrating smarter logistics solutions to address these gaps. Technologies such as Automatic Guided Vehicles (AGVs) are instrumental in warehouse management, reducing handling and transportation costs by replacing traditional forklifts (Song et al., 2020). Additionally, blockchain technology provides a secure and transparent method for tracking products through the supply chain, ensuring traceability and reducing inefficiencies (Zhan et al., 2022). Drones also enhance logistics by offering labour cost reduction, farm monitoring, and data collection, contributing to increased agricultural productivity. These drones are categorised based on their positioning, sensing, spraying, and pollination functions, collectively improving decision-making and yield (Chung, 2021). Furthermore, e-grocery platforms and cold storage distribution centres represent emerging trends that improve logistical efficiency, especially with real-time data integration that reduces fulfilment costs by as much as 34% (Ding et al., 2021). These technological advancements, inspired by solutions from other industries, are set to transform agricultural logistics, optimising resource use and delivery timelines.

Precision Farming Techniques

Today, agricultural food production has evolved significantly, transitioning from manual labour to a highly technological and data-driven industry. This shift is primarily seen in the adoption of Precision Farming or Smart Agriculture, which leverages advanced tools and techniques to enhance the efficiency of agricultural processes (Sidhu et al., 2021). Precision farming focuses on optimising the use of crucial farm resources, such as water, fertilisers, and pesticides, and monitoring climatic conditions to determine the best time for planting and managing crops throughout their lifecycle (Lakhiar et al., 2024). The benefits of precision agriculture extend beyond resource efficiency to include significant environmental and economic advantages. For example, technologies like remote sensing, GPS-guided machinery, automatic irrigation systems, and soil sensors have increased water use efficiency by 26% to 39%. In comparison, crop productivity can improve by 15% to 30%. Moreover, precision irrigation can reduce agricultural runoff by 80%, aligning with the goals of sustainable farming by minimising environmental impacts (Bwambale et al., 2022).

Economically, precision farming yields substantial returns, with farmers reporting an increase in profits of $16 to $100 per hectare due to improved resource management and labour savings (Alharbi et al., 2024). However, despite its many advantages, the high initial costs of adopting precision farming technologies, along with challenges such as data protection, interoperability between devices, and a lack of sensors, present significant barriers to widespread implementation (Lakhiar et al., 2024; Bwambale et al., 2022). These obstacles hinder the adoption of precision farming and its integration with smart logistics, which could further enhance agricultural supply chain efficiency. While precision agriculture offers a path to economic and environmental sustainability, overcoming these implementation challenges is crucial for these technologies' broader adoption and success in modern agricultural practices.

Overview and Benefits

Precision agriculture technologies have been successful in the development of systems providing crop monitoring. Major benefits of precision agriculture are managing variability between and within fields depending on specific climatic, water, and soil conditions at the lowest possible cost. Precision farming also targets the problems caused by the old-fashioned one-size-fits-all approach. This strategy does not work in situations where no one field is similar.

Precision agriculture is an outgrowth of science and engineering; computer vision, sensor technology, geospatial analysis, and GIS play an essential role. Smart technologies, including GPS equipment, remote sensors, and the internet, provide information that can greatly help farmers decide. Weather predictions and available moisture sensors inform the irrigation scheduling system based on the estimated impact on the plants. These sensors reduce the wastage of water, chemicals, and other resources and infestations of pests and diseases. This means they lower operational costs and increase yields and profits for farmers. Better farm planning and assessment can be achieved by integrating farm production and interlinked transportation. There has to be an improvement in the flow of commodities in the supply chain from farm to processor to the marketplace. Technologies applied to transportation are aimed at increasing safety and efficiency. The latest technology in agribusiness coordination based on a cooperative supply chain is Precision Farming Techniques. They have revolutionised the agribusiness environment, and integrating these techniques in commodity transport logistics will improve further. Only 30% of farms have adopted some form of these techniques, mainly due to large capital outlay and restrictions due to infrastructure. However, they are interested in incorporating these techniques with logistics management. Table 1 summarises the key points on Precision Farming (Smart Agriculture), the technologies involved, and the benefits and challenges of implementation:

Table 1: Technological Innovations, Benefits, and Challenges in Sustainable Agriculture

Aspect	Description	Examples of Technologies Used	Benefits	Challenges
Definition of Precision Farming	Precision farming, or smart agriculture, uses advanced tools to enhance the efficiency of agricultural processes by optimising resource use (water, fertilisers, pesticides) and monitoring climatic conditions (Sidhu et al., 2021; Lakhiar et al., 2024).	Remote sensing, GPS-guided machinery, automatic irrigation, soil sensors	Optimises resource use increases crop yield, improves sustainability	High initial technology costs, data protection issues, and device interoperability (Lakhiar et al., 2024).
Water Use Efficiency	Technologies like automatic irrigation and soil sensors increase water use efficiency by **26% to 39%** (Bwambale et al., 2022).	Automatic irrigation systems, soil sensors	Reduces water wastage, enhances sustainability	Initial investment in technology.
Crop Productivity	Precision farming improves crop productivity by **15% to 30%** through better resource management and real-time monitoring (Bwambale et al., 2022).	GPS-guided machinery, remote sensing, soil testing and monitoring	Increased crop yields, better land management	Access to advanced equipment is often limited in developing regions.
Environmental Impact	Precision irrigation reduces agricultural runoff by **80%**, minimising environmental impacts and aligns with sustainable farming	Precision irrigation systems, GIS, remote sensing	Reduces water pollution and limits excessive use of fertilisers and pesticides.	System maintenance and operational costs (Alharbi et al., 2024).

	goals (Bwambale et al., 2022).			
Economic Benefits	Farmers report profit increases of **$16 to $100 per hectare** due to improved resource management, labour savings, and enhanced yields (Alharbi et al., 2024).	Smart machinery, yield monitors, precision seeding tools	Higher profits, lower labour costs, and better resource allocation	High cost of adoption and lack of available infrastructure in many areas (Lakhiar et al., 2024).
Key Barriers to Implementation	High technology costs, data protection concerns, device interoperability issues, and insufficient sensors hinder the broad adoption of precision farming techniques (Lakhiar et al., 2024; Bwambale et al., 2022).	Smart sensors, cloud data systems	Addressing these challenges can lead to higher adoption rates and further improvements in agricultural efficiency.	Lack of policies to support widespread adoption, data ownership issues, and limited technical support in rural areas (Sidhu et al., 2021).
Integration with Smart Logistics	Integrating precision farming with smart logistics can improve supply chain efficiency, enhance resource management, and reduce waste (Sidhu et al., 2021).	Telematics, IoT, data management systems	Improved supply chain performance, reduced post-harvest losses	Integration difficulties due to inconsistent data sharing and technology compatibility across different systems (Lakhiar et al., 2024).

This table captures the core ideas about precision farming and the technologies used, highlighting both the benefits and challenges of implementation. The economic and environmental advantages are significant, but overcoming the challenges of high costs and data management will be key to more widespread adoption.

Integration of Smart Logistics and Precision Farming

In the food industry, substantial fresh food is wasted due to inefficient logistics, mainly because of inadequate cold chain management and poor synchronisation between farming and distribution processes (Surucu-Balci & Tuna, 2021). One approach to mitigating these losses is the integration of smart logistics with precision farming. By creating farm management zones, precision farming ensures that inputs such as fertilisers and pesticides are distributed according to the crop's specific needs, thereby reducing waste and preventing the contamination of sensitive areas (Magalhães et al., 2021). Logistical networks can be optimised by aligning with the anticipated crop yields and harvest times, enabling better raw material supply and distribution schedule planning (Anand & Barua, 2022). For instance, predicting yields can help decide the best time and location to sell produce for maximum profit, while real-time monitoring at the farm level can guide cold chain operations. This real-time integration is crucial, as delays in the supply chain can lead to increased waste, especially in perishable goods (Riesenegger & Hübner, 2022). Additionally, flexible and adaptive logistics systems can improve efficiency by allowing adjustments based on real-time data from farm activities and market demand. Such a dynamic approach to logistics is essential for building sustainable agricultural supply chains that can respond to environmental and market changes effectively. Therefore, the design of these systems must account for the specific requirements of sustainability and efficiency across the entire supply chain, from the field to the final consumer (Magalhães et al., 2021; Surucu-Balci & Tuna, 2021).

Synergies and Potential Impact

The combination of modern technology in logistics and farming offers significant synergies, enabling the development of a more integrated and automated supply chain, which enhances efficiency and sustainability while reducing waste. From a logistics perspective, this integration emphasises operational efficiency and systemic improvements, while the farming perspective focuses on economic and organisational strategies (Javaid et al., 2022). Both approaches require collaboration across companies to fully harness the potential of connected systems, which involves sharing data and managing intellectual property concerns (Karunathilake et al., 2023). Key benefits of this integration include reductions in production costs through sustainable intensification, improved environmental outcomes (such as lower greenhouse gas emissions and optimised resource use), and the creation of new value chains within the agricultural sector (Balafoutis et al., 2020; Sharma et al., 2022). However, challenges remain, particularly in addressing the scientific, technical, and market-related issues necessary to implement such innovations effectively. Several case studies highlight the successes and challenges in integrating smart logistics and precision farming, showcasing the technological advances achievable in sustainable agricultural supply chains. These examples also underscore the importance of continuous innovation to keep pace with external factors like **urbanisation**, climate change, and evolving regulatory frameworks (Karunathilake et al., 2023; Sharma et al., 2022). Furthermore, stakeholder engagement through co-design and co-creation is critical for generating value within these sustainable agricultural systems (Balafoutis et al., 2020).

Case Studies and Best Practices

This section highlights six real-world projects demonstrating the integration of smart logistics and precision farming in the European Union, with projects from Finland and Slovakia and four from the Czech Republic. Each project showcases distinct strategies for optimising agricultural processes and highlights the economic, environmental, and operational benefits achieved through the adoption of advanced technologies. The case studies provide valuable insights into overcoming technical and operational challenges. Key takeaways emphasise the importance of collaboration between developers and users, particularly in providing high-quality data for continuous technology improvements (Friha et al., 2021). It is also noted that a significant obstacle to adopting new technologies is the lack of appropriate policies, which hinders the broader implementation of smart logistics systems (Javaid et al., 2022). To address this, harmonised industrial and policy-based steps are crucial for the future development of smart machines and their use in agriculture. Moreover, the lessons learned from these projects suggest that further research should evaluate the adaptability of these techniques beyond Europe, exploring their potential in diverse agricultural contexts worldwide. Additionally, a comprehensive socio-economic impact analysis, including employment opportunities and sustainability, is recommended to understand the broader effects of these technologies on the agricultural sector (Fastellini & Schillaci, 2020). Collaboration among farmers, technology developers, and stakeholders across the EU is essential for promoting knowledge sharing and enhancing the implementation of these smart systems, which are expected to advance agricultural efficiency and sustainability significantly (Gagliardi et al., 2021). Table 2 summarizing the six real-world projects that demonstrate the integration of smart logistics and precision farming in the European Union, focusing on Finland, Slovakia, and the Czech Republic.

Table 2: Integration of Smart logistics and precision farming in some European Union

Country	Project Description	Technologies Used	Economic/Environmental/Operational Benefits	Challenges/Insights
Finland	Integration of smart logistics in cold chain management for dairy products.	IoT sensors, GPS tracking, and real-time data integration.	We have improved the shelf life of perishable goods, enhanced route efficiency, and reduced carbon emissions.	Overcoming challenges in data synchronisation between logistics partners.
Slovakia	Precision farming is for optimising water usage in agriculture and is integrated with smart irrigation systems.	Smart irrigation systems, soil moisture sensors, IoT-enabled water management.	Reduction in water usage by 30%, leading to significant cost savings and increased crop yields.	Lack of government incentives for precision farming adoption.
Czech Republic	Smart logistics and automated machinery integration for large-scale grain farming.	Autonomous tractors, GPS-controlled harvesting, real-time yield monitoring systems.	Increased harvesting efficiency, reduced fuel consumption, and operational cost reductions.	High initial costs of autonomous machinery implementation.
Czech Republic	Real-time monitoring and precision spraying in vineyards for pest control using drones.	Drones with GPS, AI for precision targeting, and GIS for field mapping.	Reduced pesticide usage by 20%, decreased labour costs, and improved environmental outcomes by limiting chemical use.	Regulatory hurdles concerning drone usage in agriculture.
Czech Republic	Use of automated sorting and packaging systems in fruit logistics to reduce spoilage during transport.	Automated guided vehicles, machine learning algorithms for sorting, and cold storage systems.	Reduced spoilage by 15%, faster packaging and sorting operations, and energy savings through optimised refrigeration.	Difficulty in aligning logistics technologies with varying farm sizes and product types.
Czech Republic	Integration of smart logistics in livestock management to optimise feed delivery and health monitoring.	IoT-based livestock trackers, automated feed dispensers, and health monitoring sensors.	Improved livestock health, reduced feed waste, and optimised labour allocation.	Lack of interoperability between tracking systems and farm management software.

These case studies illustrate how integrating smart logistics and precision farming can significantly improve efficiency, sustainability, and operational cost savings. They also highlight common challenges, such as better data interoperability, appropriate policy frameworks, and the high costs of initial technology adoption (Friha et al., 2021; Javaid et al., 2022; Gagliardi et al., 2021). Further research should focus on expanding these technologies beyond Europe and assessing their broader socio-economic impacts (Fastellini & Schillaci, 2020).

Successful Implementations

Integrating smart logistics with precision farming presents numerous benefits but also faces several challenges. Among the eight key challenges are the complexity of managing real-time data, the cost of implementing innovative technologies, and ensuring collaboration across stakeholders (Javaid et al., 2022; Jerhamre et al., 2022). Two specific examples of solutions to these challenges include a smart package for oranges, designed to enhance supply chain traceability and reduce spoilage, and a traceability architecture for a commercial supply chain, which improves transparency and accountability (Karunathilake et al., 2023). A case study demonstrated how position and speed sensors, GPS, and controller area networks have been effectively integrated into supply chains. These components enhance logistics by improving operational efficiency and reducing waste (Zhang et al., 2021). Moreover, strategies were proposed to implement smart logistics in commercial enterprises, focusing on collaboration between precision agriculture and supply chain management (Sharma et al., 2022). In another project, an operational model was developed using bi-level modelling, where leadership controls key parameters for decision-making. This system showed that an integrated decision model could be more efficient than two separate models (Javaid et al., 2022). Further experimentation in packaging operations for onions involved advanced pattern recognition algorithms and robotic navigation systems, reducing packaging time and increasing accuracy (Jerhamre et al., 2022). Technological advancements in Global Positioning Systems (GPS), Geographic Information Systems (GIS), and real-time data exchange have become integral to modern precision agriculture, proving valuable across various stages of production and logistics (Karunathilake et al., 2023; Zhang et al. 2021). Although these technologies initially faced slow adoption in the late 1990s and early 2000s, they have become essential components of smart logistics, with broad stakeholder support (Sharma et al., 2022).

Conclusion

The convergence of smart logistics and precision farming presents a promising solution for enhancing sustainability in agricultural supply chains. This integration fosters greater efficiency, reduces resource wastage, and supports environmentally conscious farming practices. Case studies from European nations illustrate how advanced technologies can positively impact the agricultural sector by improving crop yields, optimising resource allocation, and minimising carbon footprints. However, the widespread adoption of these systems is hampered by barriers such as high initial investment costs, interoperability challenges, and a lack of supportive policies. Future research and development should focus on overcoming these obstacles, encouraging stakeholder collaboration, and exploring applying these techniques in diverse agricultural environments beyond Europe. The agricultural sector can move towards a more sustainable, resilient, and technologically advanced future by addressing these challenges.

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