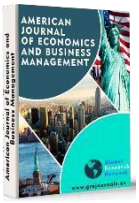

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Article

Resource Efficiency Improvement in Grain Product Enterprises: International Experience of the USA, European Union, and China, and Opportunities for Its Application in Uzbekistan

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Abstract: Resource efficiency in grain processing enterprises has emerged as a critical determinant of competitiveness, food security, and environmental sustainability. This paper investigates the best practices of three leading economies — the United States, the European Union, and China — in improving resource efficiency within grain product enterprises, and assesses the feasibility of adapting these practices to the conditions of Uzbekistan. Employing systematic literature review, comparative policy analysis, and secondary data from credible global sources like FAO, World Bank, OECD, USDA, and peer-reviewed journals, this study identifies prominent technological, institutional, and managerial strategies adopted in these regions. Our results show: the USA has made great strides in robotic crop production, Internet of Things (IoT)-allied intelligent manipulation of milling, and individual kernel management of crop; the embedded resource efficiency of the EU through the Farm to Fork Strategy is not aided by introduction of circular economy principles and reducing fertilization inputs to avoid overcap; and China has substantially enhanced its grain eco-efficiency through its telecommunications infrastructure, green technology innovation, and economies of scale. Uzbekistan, possessing a well-established grain sector and ongoing digital transformation agenda supported by Presidential Decree No. PP-257 (2023), demonstrates institutional readiness for adopting these practices, albeit constrained by legacy infrastructure, limited R&D capacity, and human capital gaps. The paper proposes a staged adaptation framework for Uzbekistan, drawing on contextually appropriate international models.

Keywords: Resource efficiency; grain processing enterprises; digital transformation; food industry; Uzbekistan; international best practices; circular economy; eco-efficiency.

1. Introduction

The grain products industry occupies a strategically vital position in the global food system. Wheat, maize, rice, and other cereals serve as primary caloric staples for billions of people worldwide, making the efficiency of their processing not merely an economic concern but a matter of food security and national policy. With the global grain processing equipment market worthUSD5.57 billionin2024, and projected to continue growing at a CAGRO f3.7%(Grand View Research) year on year, pressure on enterprises to optimize resources for production efficiency against environmental sustainability has been significantly exacerbated [1].

Resource efficiency, a concept broadly defined as the ratio of material, energy, water, and labour input to productive output, is now a matter of necessity for grain processing

enterprises in mature and emerging economies alike. Today, global food systems represent about a third of all total greenhouse gas (GHG) emissions, while the grain value chain continues to operate with important inefficiencies ranging from post harvesting losses to a high energy consuming milling and a water-reliant processing (European Commission) [2]. In this context, many of the major economies developed liquid, context-specific systems to increase the resource productivity of their grain sector.

As the world leader in the commercial grain processing industry, the US has pioneered automations, smart mills integrated with the Internet of Things, and data-driven operational optimization innovations. SUMMARY The European Union (EU) is attempting to achieve systemic transformation of food chains as part of the overarching Green Deal - more specific circular economy, Xuse of agricultural chemicals and renewable energy in processing enterprises - through a set of policies (Farm to Fork - F2F strategy). China has faced the need to feed 1.4 billion citizens double-dutyed by immense environmental pressures, and it had done its heavy lifting on innovation in green technology and deployment of infrastructure of the digital variety that has, since 2000, lifted grain eco-efficiency to unprecedented levels [3].

Since Uzbekistan, with a population of over 37 million people (Statistics Agency under the President of Uzbekistan, 2024) which continues to grow year by year, is a Central Asian country that relies heavily on its grain sector. Agriculture: 19% share of GDP and 24% of the labor force work in agriculture; the main crop is grain, particularly wheat (U.S. International Trade Administration). Wheat consumption was calculated to be 8.5 million tonnes in 2022–23 with domestic production meeting 78 per cent of demand (World Grain, 2023). Uzdonmahsulot and its previously 43 mills were the backbone of the history of state-owned grain processing in the country (World Grain, 2023), but the structural liberalization of flour production saw millers financing their own establishments, with 54% of flour coming from private millers.

Nonetheless, even with these changes, Uzbekistan's grain processing sector still requires investments in resource efficiency compared to international benchmarks. The energy intensity is high, the post-harvest losses are considerable, and the technology is only partly adopted in the processing facilities [4]. This follows the new institutional commitment to digital transformation in agricultural regulations by the Government of Uzbekistan based on Presidential Decree No. PP-257 of August 2, 2023 and Cabinet of Ministers Resolution No. 330 of August 3, 2023 (Ministry of Agriculture of Uzbekistan) defining strategic directions of digitalization across the agricultural value chain.

This paper addresses the following research questions: (1) What key strategies have the USA, EU, and China employed to improve resource efficiency in grain product enterprises? (2) What are the preconditions and barriers for adapting these international practices to the Uzbekistan context? (3) What is an appropriate framework for staged application of international resource efficiency practices in Uzbekistan's grain sector?

2. Materials and Methods

This study employs a mixed-method research design combining systematic literature review, comparative institutional analysis, and secondary data synthesis. The approach is appropriate for cross-national policy research where primary data collection at enterprise level across four jurisdictions is infeasible within a single study, and where the goal is to generate transferable knowledge for policy adaptation (Yin).

2.1 Systematic Literature Review

A systematic search was conducted across Scopus, Web of Science, PubMed/PMC, and Google Scholar databases using the following keyword combinations: ("resource efficiency" OR "eco-efficiency") AND ("grain" OR "cereal" OR "flour mill") AND ("enterprise" OR "processing" OR "industry"); and separately for each target country/region. The search was limited to peer-reviewed articles, policy documents, and

institutional reports published between 2018 and 2025, with priority given to sources published in 2021–2025 to reflect the most recent developments. After deduplication and screening for relevance, 62 sources were retained for detailed analysis [5].

2.2 Institutional and Policy Document Analysis

Key policy documents were analyzed, including: the EU Farm to Fork Strategy (European Commission, 2020); the USDA Economic Research Service reports on the U.S. grain sector; China's National Bureau of Statistics agricultural data; and Uzbekistan's Presidential Decree No. PP-257 (2023), Cabinet of Ministers Resolution No. 330 (2023), and the Development Strategy for New Uzbekistan 2022–2026. OECD reports on Uzbekistan's investment climate and digital economy (2023, 2024) were also incorporated.

2.3 Comparative Framework

International practices were analyzed across five resource efficiency dimensions: (i) energy efficiency; (ii) raw material utilization and by-product valorization; (iii) water efficiency; (iv) digital and automation technologies; and (v) institutional and regulatory frameworks [6]. These dimensions are aligned with the OECD's resource productivity framework and the European Environment Agency's monitoring indicators for resource efficiency in food chains.

2.4 Adaptation Assessment for Uzbekistan

The feasibility of applying each identified international practice to Uzbekistan was assessed using a structured matrix that considered: (a) technological readiness (availability of infrastructure and skills); (b) institutional readiness (regulatory and policy alignment); (c) economic feasibility (cost-benefit considerations for Uzbek enterprises); and (d) socio-cultural fit (compatibility with existing sector structures and labor markets). This approach draws on the Technology Adoption Model (Davis) and the contextualized institutional transfer framework proposed by Dolowitz and Marsh (2000) [7].

3. Results

3.1 Resource Efficiency Practices in the United States

The United States is home to a mature and highly consolidated grain processing industry. The flour-milling sector alone is valued at approximately USD 14.9 billion (GFM Dhaka), dominated by a small number of large integrated enterprises with substantial capital investments in modern technology. There are three main mechanisms through which American grain enterprises have made huge improvements in resource efficiency.

Advanced automation and smart milling, for example, have drastically changed operational efficiency [8]. Contemporary U.S. mills use roller milling systems linked with computerized control systems that regulate temperature, moisture content, and grinding speed in real time and thereby minimize human error and continuously maximize energy usage (NexTech Agri Solutions). Automated sorting technologies evolved from rudimentary optical scanners to multi-spectral infrared scanning systems with the ability to differentiate contaminants and damage grain at a level not previously achievable (GFM Dhaka).

Secondly, the acceptance of the idea of Internet of Things (IoT) and Artificial Intelligence (AI) in processing facilities in America helped to make possible the creation of the so-called 'smart mills'. IoT sensors, data analytics platforms, and cloud-based monitoring systems are installed in facilities that collect huge amounts of real-time operational data. Using predictive analytics, millers can predict equipment failures, order maintenance ahead of time, and minimize expensive downtime — an important win in an efficiency-oriented environment where unanticipated stoppages can set big mills back hundreds of thousands of dollars a day (Food Business Review) This advances towards real-time grain tracking and automated grain grading not just in storage but also systems driven by AI put forward smart inventory management (Rice21) [9].

The third aspect is the major focus being put on energy efficiency. Some next-generation roller mill designs utilize up to 30% less energy than designs just a decade ago (GFM Dhaka). Automation systems that accurately adjust feeding rate save power usage and improve equipment longevity. (AgriTech Tomorrow) Variable speed drive (VSD) technology, which enables mills to vary motor speed based on real processing needs instead of running on fixed speeds, has seen quantifiable decreases in energy consumption at mills without losing product quality.

By-product valorization is also advancing in the U.S. context. Grain processing generates significant volumes of bran, germ, straw, and other co-products that, when properly processed, yield nutraceuticals, animal feed ingredients, bioplastics feedstocks, and bio-energy (NexTech Agri Solutions) [10]. The integration of big data and IoT to optimize resource flow paths in by-product processing has been highlighted as a key innovation driver in the literature (Frontiers in Sustainable Food Systems).

3.2 Resource Efficiency Practices in the European Union

The European Union's approach to resource efficiency in grain and food processing enterprises is distinctive in its systemic, policy-driven character. Rather than relying predominantly on market-led technology adoption, the EU has embedded resource efficiency into a comprehensive regulatory and strategic framework.

The Farm to Fork (F2F) Strategy, adopted as a cornerstone of the European Green Deal in May 2020, represents the EU's most comprehensive food systems policy initiative. It specifically focuses on: promoting implementing aspects of the circular bio-based economy and energy efficiency solutions; using renewable energies within food processing; reducing food loss and waste; and creating a climate-neutral food chain in Europe by 2050 (European Commission). These goals are to be turned into an operational framework to 2023–2027 using the new Common Agricultural Policy (CAP), effective as of January 2023, which links direct financial subsidies to sustainability performance (Springer Nature).

In terms of specific targets, the objectives translate into resource efficiency results that comply with EU strategy, especially in the grain processing sector. Directed by the EU industrial regulations on energy efficiency obligations, grain processors are moving to recover heat, use energy efficient motors or integrate renewable energy [11]. Through its actions to allow bio-refineries that can produce bio-fertilisers, protein feed, bio-energy and bio-chemicals from processing by-products, thereby creating new value streams from previous waste, the F2F Strategy explicitly promotes the production for all four biobased products (EU SWITCH to Green, 2020). The EU's Circular Economy Action Plan (CEAP) also aims for less packaging and more recyclability in the food chain.

The F2F aims for a 50% reduction in the use and risk of chemical pesticides by 2030, and a 20% reduction in fertiliser use — target changes that impact the resource intensity of the grain production cascading into processing chains (Smart Food Safe). While there are gaps in the implementation of EU's F2F Strategy and while some measures still do not have legislation to support them (European Parliament Think Tank), the intended orientation towards a resource-efficient direction is preserved in the strategic dialogue launched in January 2024 on the future of EU agriculture (European Commission).

Arguably, the EU experience shows that making resource efficiency a cornerstone of mandatory corporate sustainability reporting adds value [12]. The Corporate Sustainability Reporting Directive (CSRD) came into force on 5 January 2023 and obliges big firms to disclose their sustainability performance — so far as it relates to the resource consumption and emissions, and will be implemented from financial year 2024 with the first reports appearing in 2025 (AGRINFO Platform, 2025). It establishes accountability mechanisms that prompt grain processors to map their supply chain resources and track efficiency indicators.

Quantitatively, the EU produced 299.3 million tonnes of cereal grains in 2019, accounting for more than half of this in wheat (Clean Energy Wire). The scale of production, combined with strict sustainability regulations, has pushed EU grain processors toward economies of scale and resource efficiency simultaneously [13]. The share of agri-food systems in total EU emissions stood at 32% in 2020, and the EU targets a 40–60% reduction in agricultural emissions by 2040 (Heinrich Böll Stiftung), providing a powerful institutional driver for efficiency across the processing chain.

3.3 Resource Efficiency Practices in China

China's grain sector presents a unique profile: the world's largest grain producing and consuming nation, accounting for 686.53 million tonnes of total grain output in 2022 — the seventh consecutive year of output exceeding 650 million tonnes (PMC). Faced with simultaneous pressures of population growth, environmental degradation, water scarcity, and rising production costs, China has pursued an aggressive green technology and digitalization strategy.

China's grain production eco-efficiency has improved substantially since 2000, despite the overall level still being characterized as relatively low and regionally uneven (Frontiers in Environmental Science). Between 2001 and 2021, total crop production increased by 34.1% with only a 7.3% expansion in total cropland area — a direct measure of rising resource productivity attributable to improved cultivars and high-cultivation techniques (FASE Journal) [14]. Annual fertilizer applications reached the highest at 60.2 Mt in 2015 and reduced to 50.8 Mt by 2022 — a decrease of over 15 % — resulting from the synergistic effects of policy promotion and scientific advances in nutrient management technologies (FASE Journal, 2025).

The key here is China's investment in digital infrastructure. Reporting in Frontiers in Sustainable Food Systems (2024), strong digital infrastructure enhances agricultural productivity and eco-efficiency through greater efficiencies in knowledge exchange and help in scaling new technologies. Digital twin technologies emulate agricultural systems in real-time to support decisions for resource optimization before their actual application [15]. Through the synergistic, substitution and penetration effects of the digital economy in China, it has promoted the emergence of new forms of governance and production, and improve the grain supply chain efficiency (Frontiers in Sustainable Food Systems).

Using big data and the Internet of Things with precision agriculture technology can help grain producers and processors have precise control over their water, fertilizers and pesticides, which reduces input waste and improves output quality and yield (Frontiers in Sustainable Food Systems). Early yield prediction based on machine learning aids the optimization of crop management and lowers post-harvest losses, thereby increasing the effective yield available for processing.

Those technologies require large investment, which does not seem easy for small and medium-sized enterprises, as the first bottleneck of China's grain industry lies in that there are too many SMEs at the processing enterprise level (Frontiers in Sustainable Food Systems). In fact, the Chinese government has also tried to introduce policies focusing on mechanization, scaling, and integration of technology in an attempt to enhance GSC efficiency. The 2024 Central Document No.1 clearly highlighted the need to strengthen grain production and regulation capacity as a cornerstone of food security.

In China, evidence has shown that environmental regulation is an important engine of resource efficiency enhancement. To date, empirical research results support that the implications of the Porter Hypothesis apply to the sphere of agricultural development in China — stringent environmental regulation motivates farmers and processors to invest or innovate green technology and sustainable production (Frontiers in Environmental Science) [16]. Recent evidence highlights the greater potential of integrated crop and soil management, reaching up to 30 per cent reduction of reactive nitrogen loss and 11 per cent reduction of greenhouse gas emission against conventional practices (FASE Journal).

3.4 Comparative Summary of International Practices

Table 1 presents a structured comparative summary of the principal resource efficiency mechanisms identified across the three jurisdictions.

Dimension	USA	European Union	China
Energy Efficiency	Automation, VSD technology, AI-driven optimization; up to 30% energy reduction in modern mills	Renewable energy integration, heat recovery, bio-refinery co-generation; driven by Green Deal targets	IoT-based precision management; reduced fertilizer use (−15.5% 2015–2022)
Raw Material Utilization	By-product valorization (nutraceuticals, bioplastics); IoT-optimized resource flows	Circular bio-economy: by-products → bio-fertilizers, bioenergy, bio-chemicals	Green cultivation tech: 34.1% production increase with only 7.3% land expansion (2001–2021)
Digitalization	Smart mills with IoT, AI, predictive maintenance, real-time monitoring	Precision farming supported by Copernicus/Galileo satellite data; digital traceability	Digital infrastructure investment; digital twins; digital economy penetration of grain supply chain
Institutional Framework	Market-led, R&D private sector; USDA technical standards and data provision	CAP 2023–2027, Farm to Fork Strategy, CSRD mandatory sustainability reporting	State-led policies; environmental regulation (Porter Hypothesis effect); scaling incentives
Water Management	Precision moisture monitoring; advanced conditioning systems	Nutrient management action plans; reduced runoff pollution targets	Drip irrigation, water-saving technologies; IoT-based irrigation optimization

Table 1. Comparative resource efficiency mechanisms in the USA, EU, and China grain sectors.

3.5 Uzbekistan's Current Position and Readiness for Adoption

Uzbekistan's grain sector in 2024 produced 9 million tonnes of grain and is characterized by a dual structure: the legacy state-owned Uzdonmahsulot holding (43 mills) and an expanding private sector, with approximately 160 new private grain processors established in recent years (World Grain; U.S. ITA). Wheat consumption demand of approximately 8.5 million tonnes annually places considerable pressure on both domestic production and processing efficiency.

Institutionally, Uzbekistan has established a supportive policy environment. Agriculture accounts for 19% of GDP and 24% of employment (U.S. ITA). The Presidential Decree No. PP-257 of August 2023, and the accompanying Cabinet of Ministers Resolution No. 330, provide explicit strategic direction for digital technology adoption in the agricultural sector, including grain (Ministry of Agriculture of Uzbekistan) [17]. From 2021 to 2024, state support mechanisms encompassed preferential loans, agricultural machinery subsidies, technical training, and land rationalization programs. By 2024, over 200 agro-clusters and 44,000 farming households were actively utilizing digital platforms (Ministry of Agriculture of Uzbekistan).

Uzbekistan's digital economy is expanding. In 2023, the IT sector output reached 8.5 trillion sum (approximately USD 690 million), a year-on-year increase of 1.2 times (AICT). The OECD (2023) has noted that reforms across digital investment, regulatory liberalization for FDI, and WTO accession progress are positioning Uzbekistan toward a more open market economy — conditions that improve the absorption of international resource efficiency practices [18].

However, significant barriers remain. The country's agricultural digital transformation is still at an early stage, particularly at the enterprise (processing facility) level (E3S Conferences). Legacy infrastructure in state-owned mills presents technological gaps [19]. Human capital in digital skills lags OECD averages, as documented in OECD analyses of Uzbekistan's business climate (OECD). Moreover, water scarcity is severe — agriculture consumes 90% of Uzbekistan's water resources (U.S. ITA) — making water efficiency a particularly acute resource efficiency challenge with no direct parallel in the wealthier contexts of the USA or EU.

The switch to market pricing for grain in June 2022 was a critical enabling reform, as it aligns producer and processor incentives toward efficiency more directly than the previous state-subsidized system allowed (World Grain). The government has also announced targets for expanding agro-processing capacity (fruit and vegetable processing from 3,488 thousand tons in 2024 to 4,480 thousand tons in 2027 under Presidential Resolution PP-136, April 2025) — signaling commitment to industrial upgrading across the food processing sector.

3.6 Adaptation Framework for Uzbekistan

Based on the comparative analysis, a three-stage adaptation framework is proposed for Uzbekistan's grain processing enterprises:

Stage 1 — Foundational Infrastructure (Years 1–3): Prioritizing investments that address immediate bottlenecks without requiring advanced digital skills. Key measures include: modernization of roller mill systems and introduction of automated moisture control; adoption of energy-efficient motors and VSD technology (drawing on the USA model); establishment of basic quality monitoring standards and food safety traceability systems; and regulatory requirements for basic sustainability reporting by large processors (inspired by the EU CSRD approach, adapted to Uzbekistan's scale).

Stage 2 — Digital Integration (Years 3–6): Building on foundational infrastructure to introduce data-driven operations [20]. Key measures include: deployment of IoT sensors for real-time monitoring of energy use, grain throughput, and moisture levels across processing facilities; development of a national grain sector digital platform integrating processing data (analogous to China's information systems supporting GSC management); training programs for mill operators and managers in data analytics and smart operations; and fiscal incentives for private millers adopting certified resource efficiency technologies.

Stage 3 — Systemic Transformation (Years 6–10): Embedding resource efficiency as a systemic institutional feature of the sector [21]. Key measures include: by-product valorization programs incentivizing circular economy practices in grain processing (EU bio-refinery model adapted to local grain mix); integration of Uzbekistan's grain processing sector into regional supply chain traceability systems supporting export market access; green finance instruments (concessional loans and grants linked to verified resource efficiency improvements); and institutional support for grain processing enterprise clusters modeled on China's agro-cluster development experience.

4. Discussion

The findings of this study reveal both the richness of internationally available resource efficiency practices and the complexity of contextual adaptation. Comparing the USA, EU, and China underscores that no single model is universally transferable: each

jurisdiction's trajectory has been shaped by distinct factor endowments, institutional architectures, and development trajectories.

The USA model's strength lies in market-driven innovation, where competitive pressure and access to sophisticated capital markets have driven rapid adoption of IoT, AI, and advanced automation in large-scale grain processing. Because publicly-funded institutions, controlled by the state, dominated Uzbekistan's grain sector until very recently, this model is not one that can be easily recreated in its entirety [22]. However, while the technical innovations — most notably, VSD technology and predictive maintenance systems — are available from Chinese suppliers at progressively lower cost points and lend themselves to progressive introduction without a full-blown smart mill transformation.

The most transferable component of the EU model for Uzbekistan is the institutional design: the incorporation of policy mandates, public procurement standards, and sustainability reporting requirements into legislation to offer systematic incentives for resource efficiency instead of depending entirely on voluntary compliance. The Uzbek government has shown willingness to leverage regulatory instruments in the grain sector — e e.g. the market price reform of 2022 and the digital transformation decrees of 2023 — indicating institutional capacity alignable to EU-style sustainability governance at the required scale.

Of all countries, China might be the one with the most directly instructive experience for Uzbekistan, attributable to structural similarities: both countries exhibit large agricultural sectors; the importance of state enterprises alongside emerging private sectors; and the challenge of achieving greater efficiency at scale across many SME processors [23]. China has achieved an increase of 34.1% in grain production despite a land expansion of only 7.3% so its experience shows that even in markets constrained by land and with initially high fragmentation rates in the farm structure, technology-driven efficiency gains in terms of resources are possible. Uzbekistan also faces land constraint challenges (1.4 million hectares of wheat harvested area in 2022-23), and therefore, China's pathway of intensification is particularly relevant.

In the context of Uzbekistan, special attention should be paid to the dimension of water efficiency. Even by regional standards, agriculture's 90% share of national water use (U.S. ITA) is acute, and climate change is projected to further exacerbate water stress in Central Asia. Consequently, water productivity metrics thus need to be directly integrated into resource efficiency programs for Uzbekistan's grain sector —both at field-level production (where IoT based irrigation optimization can be highly effective) and also in processing facilities where advanced moisture manage ment technology can help to reduce water use in rice conditioning and cleaning [24].

We must not underestimate the institutional barriers to adaptation. However, Uzbekistan is still in a relatively early stage of transition towards an open and competitive market economy, which is characterized by low dynamism of the private sector, along with significant structural obstacles in respect of digital skills (OECD). These limits indicate that the stepwise approach outlined in the three-stage framework should be undertaken at a feasible tempo, the prioritization of Stage 1 measures should be made and supported by significant investment in human capital development, a notion reiterated by the estimate of Uzbekistan's digital skill level having the run of nearly a quarter of century lagging behind that of the OECD average.

State subsidies to the grain market have been dropped since June 2022 — a basic reform that allows market-driven truthful pricing to take place — this creates the basis of an incentive structure for efficient investment in resources. On market terms, resource efficiency as a means of operational cost with the effect of improving stock is a direct commercial necessity instead of a policy wish. This conforms with both the theoretical foundation of the Porter Hypothesis, which has been empirically verified in China's grain

sector (Frontiers in Environmental Science), and support the concept that strategically structured environment and efficiency-enforcing regulations can stimulate, rather than deter, industrial innovation and competitive advantage.

This study carries several limitations. The analysis mostly relies on secondary data, and cannot adjust for the enterprise level heterogeneity within a given jurisdiction [25]. To empirically test the adaptation framework (see section 3.1) created in this study, future research would benefit from obtaining primary firm-level data, possibly through more structured surveys targeting a sample of grain processing enterprises in Uzbekistan. Furthermore, the agility of technologies to change — especially in AI and IoT applications — implies that certain specialized technology assessments may shift considerably over a short duration.

4. Conclusion

This study has examined international resource efficiency practices in grain product enterprises across the USA, European Union, and China, and assessed their applicability to Uzbekistan. The principal conclusions are as follows.

First, all three leading economies demonstrate that resource efficiency improvements in grain processing are achievable through a combination of technological innovation (smart automation, IoT, AI, precision agriculture), institutional design (mandatory sustainability reporting, circular economy frameworks, policy incentives), and systematic investment in digital infrastructure. These are not mutually exclusive but mutually reinforcing pathways.

Secondly, Uzbekistan bring substantial preconditions for the adoption of international resource efficiency: from a government pledged to digitalisation of agriculture (e.g. Decree PP-257, 2023), an increasing share of private mills (54% of flour production in 2023), liberalisation of grain markets (from June 2022), growing framework of a digital economy (IT sector output USD 690 million in 2023), and established agrogroup features. These are real live institutional and sectoral adaptation assets.

Third, while our path of innovating new solutions on a small scale and then taking them to major state-owned mills comes closest to the USA or EU model (none of which has been fully adopted), the constraints in Uzbekistan to wider adopt the innovations are legacy infrastructure in state-owned mills, weak digital skills for agricultural workforce, lack of enterprise-level R&D and, last but not least, pressing water scarcity which has created specific demand for resource efficiency in agriculture and irrigation. These restrictions require an approach that is both gradual and suited to the context.

The three-stage adaptation framework proposed — modernization of foundational infrastructure, digital integration and systemic transformation — provides a route map rooted in international evidence and adjusted for Uzbekistan's realities in institutional limitations. This will involve coordinated efforts across government (having the regulatory and fiscal framework), the private sector (technology adoption investment), international development partners (technical assistance and concessional financing), and academic institutions (training human capital and local applied research).

While resource efficiency should not be regarded as a side discretionary affair but rather as a strategic industrial priority, in order for Uzbekistan to unlock potential in its grain sector — from feeding an ever-growing population that is expected to surpass 41 million people by 2030, to supplying export markets in Afghanistan and beyond. The international examples outlined in this study show this change is needed and possible.

REFERENCES

[1] AICT (Agency for Innovative Development of Uzbekistan). (2024). Uzbekistan Digital Economy Overview and Vision 2030. Tashkent: AICT. Available at: https://aict.uz/caict_uzbekistan_digital_economy_overview_vision_2030.pdf

[2] AGRINFO Platform. (2025). Overview: EU Farm to Fork and Green Deal Initiatives. Retrieved from https://agrinfo.eu/book-of-reports/overview-eu-farm-to-fork-and-green-deal-initiatives/

[3] AgriTech Tomorrow. (2024). Energy-efficient milling: Reduce energy costs and improve sustainability through feed mill automation. Retrieved from https://www.agritechtomorrow.com/story/2024/02/energy-efficient-milling

[4] Chen, R., Li, Y., & Wang, X. (2022). Digital infrastructure construction and agricultural productivity. Journal of Agricultural Economics, 73(2), 345–367. https://doi.org/10.1111/1477-9552.12467

[5] Clean Energy Wire. (2021). EU's Farm to Fork Strategy: Impacts on climate, productivity, and trade. Retrieved from https://www.cleanenergywire.org/factsheets/eus-farm-fork-strategy-impacts-climate-productivity-and-trade

[6] Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly, 13(3), 319–340. https://doi.org/10.2307/249008

[7] Dolowitz, D. P., & Marsh, D. (2000). Learning from abroad: The role of policy transfer in contemporary policy-making. Governance, 13(1), 5–23. https://doi.org/10.1111/0952-1895.00121

[8] Du, Y., Zhang, Y., & Liu, C. (2023). Environmental regulation, green technology adoption, and agricultural eco-efficiency in China. Journal of Cleaner Production, 398, 136456. https://doi.org/10.1016/j.jclepro.2023.136456

[9] E3S Conferences. (2023). Digital transformation of the agricultural sector in Uzbekistan (Vol. 449). https://www.e3s-conferences.org/articles/e3sconf/pdf/2023/97/e3sconf_bft2023_02003.pdf

[10] European Commission. (2020). Farm to Fork Strategy: For a fair, healthy and environmentally-friendly food system. COM/2020/381. Brussels: European Commission. Retrieved from https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en

[11] European Parliament Think Tank (EPRS). (2024). EU 'Farm to Fork' Strategy: State of Play. Retrieved from https://epthinktank.eu/2024/02/13/eu-farm-to-fork-strategy-state-of-play/

[12] Food Business Review. (2025). Advancing precision and efficiency in grain milling technology. Retrieved from https://www.foodbusinessreview.com/news/advancing-precision-and-efficiency-in-grain-milling-technology-nwid-1427.html

[13] Frontiers in Environmental Science. (2026). Eco-efficiency and its determinants of major grain-producing areas in China. https://doi.org/10.3389/fenvs.2025.1597439

[14] Frontiers in Sustainable Food Systems. (2024a). Leveraging digital infrastructure for sustainable grain production: Evidence from China. https://doi.org/10.3389/fsufs.2024.1440321

[15] Frontiers in Sustainable Food Systems. (2024b). How the digital economy enhances the grain supply chain resilience in China. https://doi.org/10.3389/fsufs.2024.1439593

[16] Frontiers in Sustainable Food Systems. (2025). Enhancing resource efficiency and value addition in food and agricultural by-product processing: A green recycling approach. https://doi.org/10.3389/fsufs.2025.1589807

[17] FASE Journal (Frontiers of Agricultural Science and Engineering). (2025). Innovations in green technology for increasing major grain crop production and efficiency in China. https://doi.org/10.15302/J-FASE-2025633

[18] GFM Dhaka. (2025). What is grain-milling technology like today and tomorrow? Retrieved from https://gfmdhaka.com/news/what-is-grain-milling-technology-like-today-and-tomorrow

[19] Grand View Research. (2024). Grain Processing Equipment Market | Industry Report, 2030. Retrieved from https://www.grandviewresearch.com/industry-analysis/grain-processing-equipment-market

[20] Heinrich Böll Stiftung. (2024). Sustaining tomorrow: The imperative for the EU to uphold its 2030 goals for a sustainable food system. Retrieved from https://eu.boell.org/en/2024/03/20/eu-sustainable-food-system

[21] Li, Y., Wang, X., & Chen, L. (2024). R&D investment, technological progress, and resource allocation efficiency in China's grain sector. Agricultural Economics, 55(1), 89–105. https://doi.org/10.1111/agec.12847

[22] Ministry of Agriculture of Uzbekistan. (2024). Digitalization of agriculture in Uzbekistan increases the competitiveness of the industry. Retrieved from https://uzbekembassy.com.my/eng/news_press/digitalization_of_agriculture_in_uzbekistan_increases_the_competitiveness_of_the_industry.html

[23] NexTech Agri Solutions. (2024). Optimizing grain milling operations: Key strategies for efficiency. Retrieved from https://www.nextechagrisolutions.com/blog/optimizing-grain-milling-operations-key-strategies-efficiency/

[24] NexTech Agri Solutions. (2025). How to reduce energy costs in grain milling with advanced solutions. Retrieved from https://www.nextechagrisolutions.com/blog/reduce-energy-costs-grain-milling-solutions/

[25] OECD. (2023). Insights on the business climate in Uzbekistan. Paris: OECD. https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/05/insights-on-the-business-climate-in-uzbekistan_9ac46b98/317ce52e-en.pdf