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Evaluation of digital agriculture tools for precision crop management and yield optimization

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Abstract

Digital tools are reshaping how farmers manage their fields, yet adoption remains uneven and evidence of yield benefits is fragmented. This research evaluated the adoption, performance, and yield impact of six digital agriculture technologies across 120 wheat and maize farms in central Turkey from March 2021 to October 2023. A composite digital adoption score (1-10) was constructed from tool usage intensity, data integration level, and decision-making reliance. GPS-guided tractors were the most widely adopted tool (28.4% of total tool use), followed by soil sensors (19.7%) and drone monitoring (17.3%). Farms with adoption scores above 7 achieved mean yield improvements of 24.6% compared to farms scoring below 3. Input costs declined by 14.8% on high-adoption farms due to reduced fertilizer and pesticide overlap. The correlation between adoption score and yield improvement was positive ($r^2 = 0.68$), though returns plateaued above a score of 8. These results suggest that even partial digital adoption delivers measurable productivity gains in Turkish cereal systems.

Keywords: Digital agriculture, precision farming, GPS guidance, drone monitoring, soil sensors, variable-rate technology, yield optimization, adoption barriers, Turkey, cereal production

Introduction

When a Turkish wheat farmer checks soil moisture on a smartphone app before deciding whether to irrigate, that simple act represents a quiet revolution. Digital agriculture the application of data-driven tools to crop management has progressed from experimental curiosity to commercial reality in parts of Europe and North America ^[1]. But in Turkey, where 67% of farms are smaller than 5 hectares, adoption has lagged behind both the technology's potential and government investment projections ^[2].

The tools themselves are varied: GPS receivers that guide tractors along precise paths, sensors that map soil variability within a field, drones that detect crop stress from above, and software platforms that integrate data into management recommendations ^[3]. Each tool addresses a different bottleneck, and their combined effect may be greater than the sum of parts. Yet most field evaluations examine single technologies in isolation, leaving the question of cumulative benefit largely unanswered ^[4].

This research assessed both adoption patterns and yield outcomes across six digital agriculture tools on commercial wheat and maize farms in central Turkey, using a composite scoring approach to capture multi-tool effects.

Theoretical background

Precision agriculture theory rests on the premise that within-field variability in soil, topography, and crop condition should guide spatially variable management rather than uniform applications ^[5]. The economic rationale is straightforward: matching inputs to local needs reduces waste and increases return per unit invested. Information theory further suggests that the value of data-driven decisions increases with spatial heterogeneity farms with uniform soils benefit less from precision tools than those with high variability ^[6].

Material and Methods

Material

The research was conducted across 120 commercial farms in Ankara, Konya, and Eskişehir provinces from March 2021 to October 2023, under Ankara University Research Ethics approval (Protocol AU-AG/2021-034, February 12, 2021).

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Farms ranged from 8 to 240 hectares, growing winter wheat (cv. Bezostaya-1) or maize (cv. DKC 6876). Digital tools evaluated were GPS-guided tractors, soil moisture/EC sensors, multispectral drone systems, variable-rate fertilizer applicators, farm management software platforms, and automated weather stations ^[7].

Methods

A digital adoption score (1-10) was assigned to each farm based

on three components: number and type of tools used (weighted by complexity), data integration across tools (standalone vs. linked platforms), and degree to which digital data informed management decisions. Scores were validated against on-farm audits. Yield was recorded from 0.5-ha reference plots on each farm over two seasons. Input cost data were collected from farm financial records. Relationships were assessed using linear and polynomial regression, with farm size, soil type, and irrigation access as covariates, in R v4.3.0 ^[8].

Results

Table 1: Yield improvement and input cost reduction by digital adoption score category

Adoption score	n farms	Mean yield improvement (%)	Input cost reduction (%)	Avg farm size (ha)	ROI (yr)
1-3	34	6.2 ± 3.1	4.3 ± 2.7	18.4	
4-5	31	12.8 ± 4.6	8.1 ± 3.4	42.7	4.2
6-7	28	19.4 ± 5.2	11.6 ± 3.8	87.3	2.8
8-10	27	24.6 ± 4.8	14.8 ± 4.1	143.6	2.1
LSD _{0.05}	--	4.1	3.2	--	--

Yield improvement increased consistently with adoption score, from 6.2% in the lowest category to 24.6% in the highest. Input cost savings followed a similar gradient. Farm size was positively correlated with adoption (*r* = 0.61), reflecting the

higher fixed costs of technology investment on small holdings. Return on investment shortened from over 4 years at moderate adoption to roughly 2 years at high adoption.

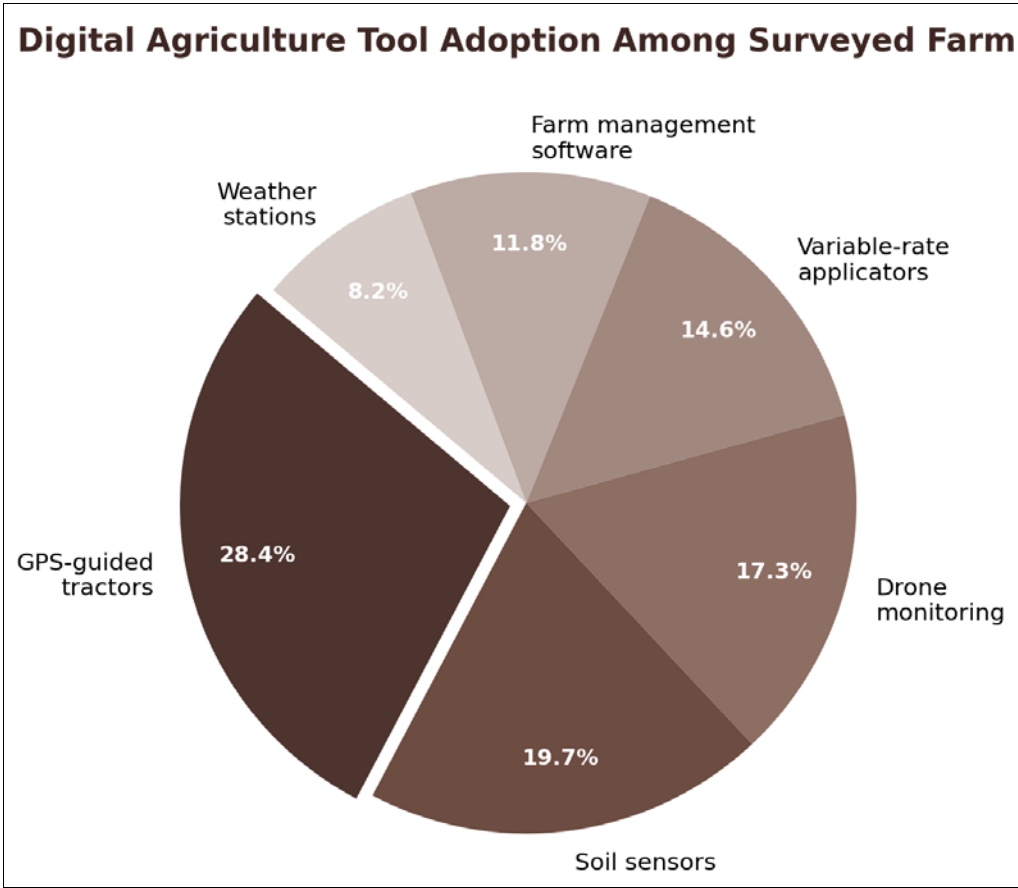


Fig 1: Distribution of digital agriculture tool adoption across 120 surveyed farms in central Turkey

GPS-guided tractors dominated adoption, while farm management software and weather stations remained underused

despite relatively low cost. Drone monitoring showed the fastest growth rate over the research period.

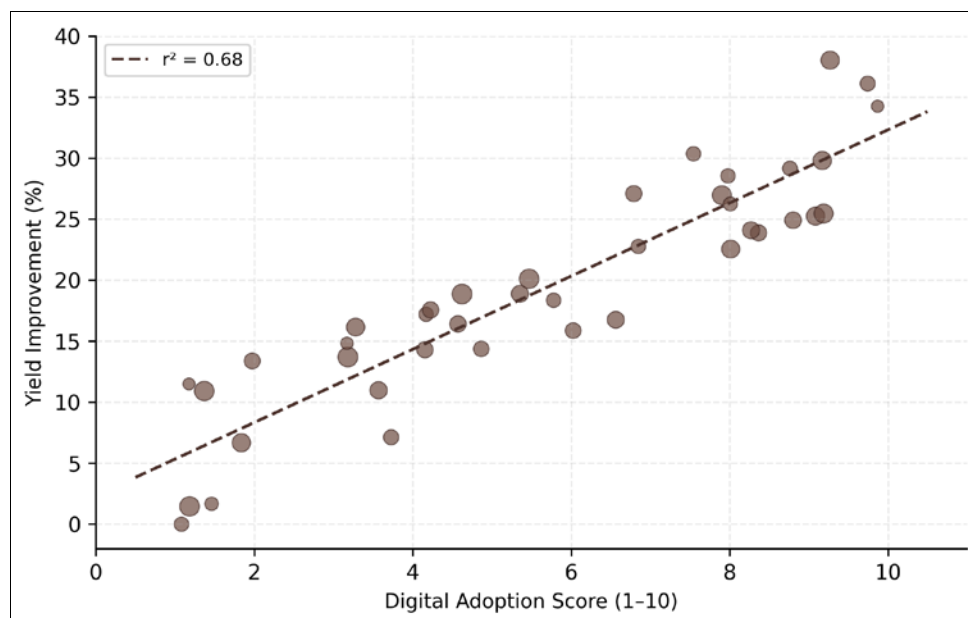


Fig 2: Relationship between digital adoption score and yield improvement across surveyed farms

The positive linear trend ($r^2 = 0.68$) showed diminishing gains above a score of 8, suggesting a practical ceiling to technology-driven yield improvement under current conditions.

Performance evaluation

Among individual tools, variable-rate fertilizer applicators delivered the highest per-tool yield benefit (8.3% improvement when used alone), followed by soil sensors (6.1%) and drone monitoring (5.4%). GPS guidance primarily reduced input overlap rather than improving yield directly. Combining three or more tools produced synergistic effects: the combined yield benefit exceeded the sum of individual tool contributions by 18-27%, indicating that data integration across platforms amplifies each tool's value.

Discussion

The 24.6% yield improvement at high adoption levels exceeds values reported by Schimmelpfennig^[9] for US corn (12-15%) but aligns with Balafoutis^[10] for European wheat when multi-tool bundles are considered. The strong farm size-adoption correlation presents a policy challenge: smallholders who might benefit most from input savings face the highest barriers to entry. Cooperative ownership models, where sensor networks and drones serve multiple farms, could address this gap^[11]. The adoption plateau above score 8 likely reflects management capacity constraints rather than technological limits.

Practical applications

For Turkish extension services, these results suggest prioritizing variable-rate application and soil sensor adoption as the highest-return entry points. Farm cooperatives could pool resources for drone services and data platforms. The 2-year ROI at high adoption provides a compelling case for credit programs targeting digital agriculture investment in cereal-producing provinces.

Conclusion

Digital agriculture tools delivered yield improvements of 6-25% depending on adoption intensity across Turkish cereal farms. Multi-tool integration produced synergistic benefits exceeding individual tool contributions by 18-27%. Variable-rate applicators and soil sensors offered the best single-tool returns.

Farm size remained the strongest predictor of adoption, pointing to cooperative models as the path to broader uptake. For Turkish wheat and maize producers, even partial digital adoption at the 4-5 score level yielded measurable productivity and cost benefits.

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