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Asma Fayaz
University Institute of Agricultural
Sciences, Chandigarh University,
Mohali, Punjab, India

Pratham Patyala
University Institute of Agricultural
Sciences, Chandigarh University,
Mohali, Punjab, India

Carbon-sensitive farming: Intelligent tools to monitor and lower field emissions

Asma Fayaz and Pratham Patyala

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Abstract

The gradual rise in atmospheric Carbon Dioxide (CO₂) levels caused by human activities has increased concerns about the environmental impact of agricultural production. Consequently, there is growing interest in farming approaches that can be useful for monitoring and reducing greenhouse gas emissions from fields. Carbon-sensitive farming emphasizes the use of intelligent tools and modern technological approaches to better understand emission patterns and improve farm management practices. This study emphasizes the potential of these tools and technologies for lowering field-level CO₂ emissions. The development of affordable carbon dioxide monitoring devices based on Non-Dispersive Infrared (NDIR) sensor technology provides a practical method for accurate and reliable measurement of CO₂ concentrations under field conditions. These devices allow farmers and researchers to participate in environmental data collection and emission monitoring. Continuous observation of field emissions also generates valuable data for informed farm management decisions. Furthermore, wider accessibility to low-cost sensing tools promotes greater participation in environmental data collection and strengthens awareness of climate and air quality issues. Overall, the integration of intelligent monitoring systems with carbon-sensitive farming practices offers a practical pathway for improving emission management, enhancing agricultural efficiency, and supporting the transition toward sustainable and low-carbon agricultural production systems.

Keywords: Carbon Dioxide (CO₂), carbon-sensitive agriculture, sustainable agriculture, field emissions, NDIR sensors

Introduction

Agriculture stands at the middle of the climate challenge because it is pretentious by climate change while it also contribute. Rising atmospheric CO₂ attentiveness have sharpened concern over the environmental footprint of food production, especially in systems where tillage, residue disturbance, irrigation, fertilizer use, and fossil-energy dependence accelerate carbon loss or amplify greenhouse gas emissions. Although methane and nitrous oxide dominate many agricultural climate assessments, field-level CO₂ still matters because it reflects the combined action of soil microbes, root respiration, crop residues, soil disturbance, moisture changes, and carbon inputs or losses across the production cycle. A carbon-sensitive farming approach therefore does not treat CO₂ as a background variable; it treats it as a measurable management signal that can help guide low-carbon production strategies (Francioni *et al.*, 2025) [8].

The practical challenge has always been measured. Conventional greenhouse gas monitoring systems are also too expensive, so much demanding technically, or so much spatially limited for wide use in farm fields. Recent advance technologies have started to change that. Low-cost CO₂ sensors, especially those are based on NDIR properties, are now evaluated and adapted for agricultural uses, including portable soil-respiration devices, low-cost automated chambers, and citizen-science-ready field instruments. On the same time, digitally worked agriculture has made it easy to connect gas measuring with soil moisture, temperature, irrigation events, crop status, remote sensing layers, and decision-support platforms. These shifts make it easier to move from daily or regular measurement toward continuous, field-relevant observation (Dubey *et al.*, 2024) [7]. This review give information on carbon-sensitive farming as a management outline supported by intelligent tools for monitoring and decreasing field-level CO₂ emissions. This paper covers

Corresponding Author:
Asma Fayaz
University Institute of Agricultural
Sciences, Chandigarh University,
Mohali, Punjab, India

the source of agricultural CO₂ emissions, the principles of carbon-sensitive farming, earlier sensor technologies, the promise of NDIR-based low-cost monitoring, continuous observation systems, data-driven farm management, mitigation strategies, social and environmental benefits, limitations, and future research needs. Mainly the aim is to show how measurement technologies can move beyond data collection alone and become part of routine low-carbon farm management (Sloan *et al.*, 2025) ^[17].

Agricultural production and field-level CO₂ emissions

Field-level CO₂ emissions in agriculture arise mainly from soil respiration, which includes microbial decomposition of soil organic matter and plant residues as well as root respiration. These processes are strongly shaped by management. Tillage increases aeration and often accelerates carbon mineralization. Irrigation alters soil moisture conditions that can stimulate microbial activity and carbon release. Fertilization affects biological activity directly and indirectly, especially when organic amendments or manure increase the supply of decomposable carbon. Crop residue management also influences whether carbon remains protected in soil or is rapidly mineralized and released. Recent field studies in maize, orchard, and mixed cropping systems continue to show that soil CO₂ flux is highly sensitive to soil disturbance, water regime, fertilization, vegetation cover, and seasonal conditions (Francioni *et al.*,

2025) ^[8]. Recent proofs also shows that agricultural CO₂ emissions cannot be understood only from annual averages. A substantial amount of carbon loss may occur during specific windows such as rewetting after dry periods, post-harvest fallows, residue incorporation, and irrigation pulses. For example, a long-term Mediterranean field study reported that soil CO₂ emissions during fallow periods differed across no-tillage and conventional-tillage plots and were influenced by temperature, soil water, and spontaneous vegetation, showing that periods outside the main crop season can still be important for carbon budgeting. This is especially relevant for carbon-sensitive farming because farms often manage visible crop growth much more closely than they manage fallow-period carbon losses (Francioni *et al.*, 2025) ^[8]. At broader system scale, agricultural emissions are also tied to input intensity. Synthetic nitrogen fertilizer systems contribute substantially to agricultural greenhouse gas emissions when production, transport, and field-use stages are considered together. Even when the field focus is specifically CO₂, carbon-sensitive farming cannot ignore upstream emissions from inputs because field decisions influence both direct and indirect carbon footprints. A monitoring-centered farming system is therefore most useful when field measurements are interpreted alongside irrigation, nutrient, residue, and machinery practices rather than as isolated CO₂ values (Shahab *et al.*, 2025) ^[16].

Table 1: Sources of CO₂ emissions in agriculture

Source of emission	Description	Key drivers	Impact on CO ₂ release
Soil respiration	Microbial decomposition + root respiration	Temperature, moisture, organic matter	Major contributor
Tillage operations	Soil disturbance increases aeration	Plowing, harrowing	Accelerates carbon loss
Irrigation events	Alters soil moisture and microbial activity	Frequency, intensity	Causes emission pulses
Residue decomposition	Breakdown of crop residues	Residue type, moisture	Short-term CO ₂ spikes
Fertilizer application	Stimulates microbial processes	Nitrogen inputs	Indirect CO ₂ increase
Fallow periods	Unmanaged soil respiration	Weed growth, moisture	Often underestimated

Note: Created by author based on Francioni *et al.* (2025) ^[8], Lal (2018) ^[12], and Paustian *et al.* (2016) ^[15]

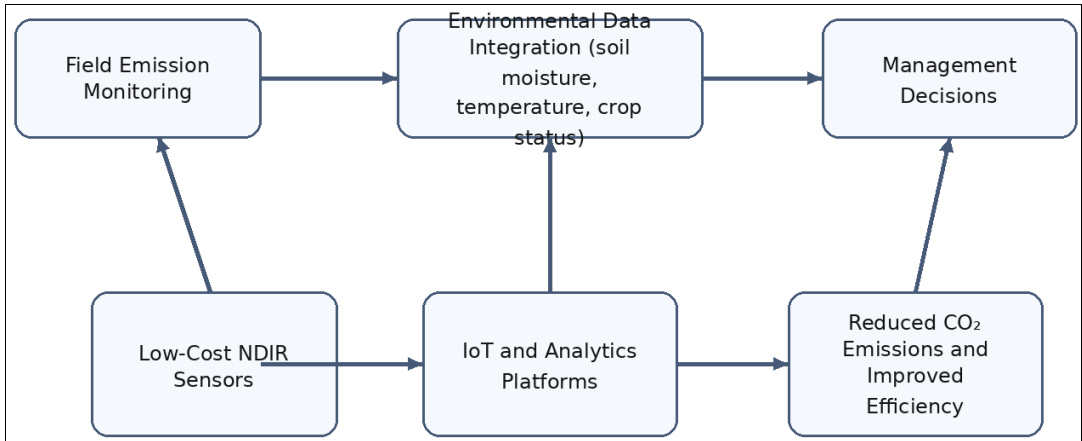
The importance of field monitoring follows from this variability. Static assumptions cannot capture how emissions differ across soil types, crop rows, orchard micro-sites, fallows, or irrigation regimes. Studies using field chambers, probes, and repeated observation have shown that even within a single field, soil CO₂ can vary strongly over time and space. For practical management, this means that monitoring under real field conditions is not optional; it is necessary if farmers and researchers want to connect emissions to actual management events and reduce them effectively (Guarrera *et al.*, 2024) ^[10].

Concept and principles of carbon-sensitive farming

Carbon-sensitive farming can be understood as a farming approach in which carbon emissions and carbon storage are treated as core management concerns rather than external reporting issues. In this framework, the farm is managed with awareness of when carbon is being conserved, when it is being lost, and how operational choices such as tillage, irrigation, fertilizer timing, and soil cover influence those outcomes. The idea is not only to measure carbon but to make carbon information usable in everyday field decisions. This gives carbon-sensitive farming a strong link to precision agriculture, climate-smart agriculture, and soil-health-based farming, but with a more explicit focus on carbon dynamics (Francioni *et al.*, 2025) ^[8]. The main goals of carbon-sensitive farming are to reduce

unnecessary field-level emissions, protect or rebuild soil carbon stocks, improve input-use efficiency, and support resilient crop production under changing climate conditions. These goals are especially important where soils are repeatedly disturbed, where irrigation is poorly matched to crop need, or where nutrient management raises biological carbon losses without equivalent productivity gains. Recent tillage, irrigation, and orchard studies show that soil carbon losses are strongly management-dependent, which means that mitigation is often possible through better timing and design rather than through radical restructuring alone (Bozóki *et al.*, 2025) ^[4]. A central principle of carbon-sensitive farming is that emission monitoring and farm management must be linked. A field sensor or chamber system has limited value if it produces data that remain disconnected from management decisions. The strongest recent work in this area has moved toward integrated systems that measure CO₂ alongside soil temperature, moisture, salinity, or nutrient conditions and then connect those signals to mobile apps, cloud dashboards, or AI-based recommendation systems. That integration helps users interpret whether a rise in CO₂ is associated with irrigation, microbial activation, residue decomposition, or soil warming. This makes the measurement actionable rather than merely descriptive (Shahab *et al.*, 2025) ^[16]. Carbon-sensitive farming also supports sustainable agriculture by shifting the focus from yield alone to yield with

environmental efficiency. A carbon-aware field management system asks not only how much biomass or grain is produced, but how much carbon is lost to achieve it and whether those losses can be reduced without sacrificing productivity. This becomes especially important as carbon markets, sustainability reporting, and climate-oriented farm programs place more value on measurable environmental performance (Francioni *et al.*, 2025) ^[8].



Note: Created by the authors based on Francioni *et al.* (2025) ^[8], Shahab *et al.* (2025) ^[16], and Sloan *et al.* (2025) ^[17]

Fig 1: Conceptual framework of carbon-sensitive farming and intelligent monitoring

Intelligent tools and modern technologies for emission monitoring

Sensor-based monitoring systems

Sensor-based monitoring is the foundation of intelligent carbon-sensitive farming. The main advantage of sensor-based systems is that they allow repeated or continuous observation at field scale, which is difficult to achieve with occasional manual laboratory analyses. In agricultural settings, gas monitoring is increasingly integrated with measurements of soil moisture, temperature, humidity, or light so that changes in CO₂ can be interpreted within their environmental context. Recent IoT-driven systems in agriculture have shown that low-cost sensor networks can provide real-time field information and link those data to management recommendations through digital platforms

(Shahab *et al.*, 2025) ^[16]. The main field-scale approaches for CO₂ monitoring include chamber-based systems, point concentration probes, and micrometeorological methods such as eddy covariance. Eddy covariance is highly valuable for landscape-scale carbon exchange but is often too expensive and infrastructure-heavy for widespread farm adoption. Chamber-based methods remain more practical for plot-scale and field-scale agricultural work because they are portable, relatively affordable, and adaptable to replicated trials and on-farm measurements. This is why much of the recent innovation in carbon-sensitive farming centers on low-cost chambers, portable systems, and chamber-linked NDIR sensors (Gottschalk *et al.*, 2024) ^[9].

Table 2: Intelligent tools for CO₂ monitoring

Technology	Working principle	Advantages	Limitations
NDIR sensors	Infrared absorption of CO ₂	Low cost, portable, real-time	Requires calibration
Closed chamber	Measures gas accumulation	Accurate field measurement	Labor-intensive
IoT sensors	Network-based monitoring	Real-time, remote access	Connectivity issues
Eddy covariance	Measures gas flux at ecosystem level	High accuracy	Expensive
Wireless sensor networks	Multi-point monitoring	Spatial analysis	Power/maintenance
Remote sensing	Satellite-based estimation	Large-scale coverage	Lower precision

Note: Created by author based on Dubey *et al.* (2024) ^[7], Zeng *et al.* (2026) ^[20], and Baldocchi (2003) ^[2]

A major strength of modern sensor systems is their capacity for continuous or high-frequency monitoring. Instead of taking one measurement per week or one set of chamber readings after a major operation, researchers and farmers can increasingly obtain time-series data that capture short-term pulses and seasonal dynamics. This is crucial because field CO₂ emissions often respond rapidly to moisture changes, warming, residue handling, or soil disturbance. Without continuous or repeated observation, those peaks may be missed and management effects may be underestimated (Francioni *et al.*, 2025) ^[8].

Non-Dispersive Infrared (NDIR) sensor technology

NDIR technology has become central to low-cost CO₂ monitoring because it offers a relatively simple, compact, and scalable way to estimate gas concentration from infrared

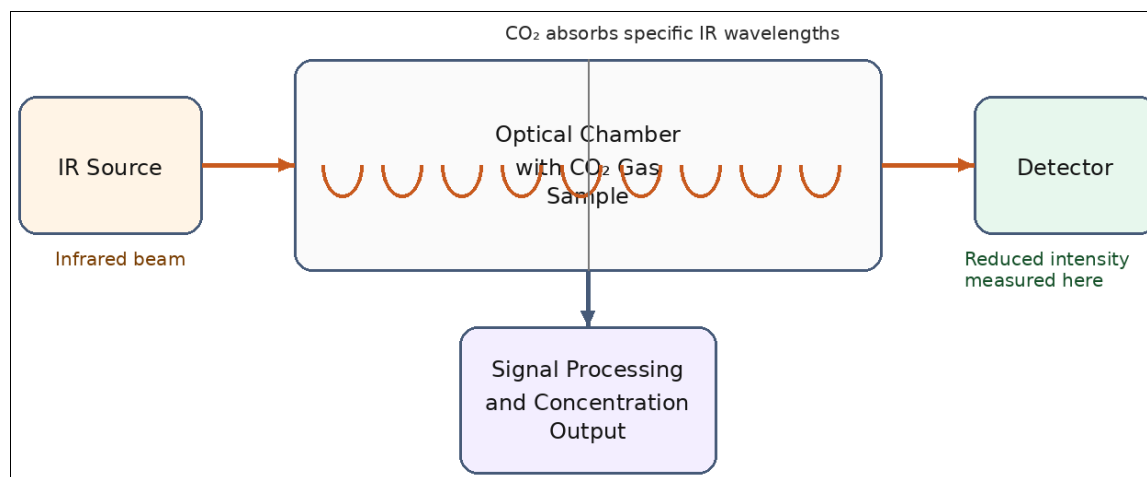
absorption. Recent agricultural development studies emphasize that NDIR sensors are attractive because they combine practical sensitivity with lower cost than many research-grade analyzers. This has encouraged their use in portable devices, automated chambers, fixed-point systems, and participatory monitoring tools (Sloan *et al.*, 2025) ^[17]. One of the most important recent developments is the growing body of evaluation work on low-cost NDIR sensors. Dubey *et al.* (2024) ^[7] compared low-cost CO₂ sensors from different price categories against a reference-grade analyzer and showed that machine-learning-based calibration could improve performance, while also highlighting clear differences among sensor models and price tiers. Cai *et al.* (2024) ^[5] likewise showed that calibration of low-cost CO₂ sensors with reference instruments and standard gases could markedly improve

performance, supporting the broader idea that affordable CO₂ monitoring is feasible when supported by strong correction protocols (Cai *et al.*, 2024; Dubey *et al.*, 2024) ^[5, 7].

These findings matter for agriculture because field conditions are rarely stable. Dust, heat, humidity, condensation, strong diurnal cycles, and changing airflow all challenge sensor performance. NDIR sensors can work well in these conditions, but the recent literature makes clear that low cost should not be confused with maintenance-free operation. Carbon-sensitive farming systems built on NDIR sensors must account for drift, environmental bias, chamber leakage, and sensor-to-sensor variation if they are to generate credible data (Dubey *et al.*, 2024) ^[7].

Recent agricultural prototypes are encouraging. Sloan *et al.*

(2025) ^[17] developed two low-cost NDIR-based agricultural CO₂ monitoring systems for citizen scientists, including an automatic opening chamber and a portable device, and reported strong calibration performance. Verma *et al.* (2026) ^[18] developed a low-cost automated soil flux chamber using a low-cost NDIR sensor and automated data logging, with explicit testing against a commercial LI-COR chamber. Zeng *et al.* (2026) ^[20] also developed a portable low-cost soil respiration system based on an NDIR sensor for continuous in situ soil CO₂ flux measurements. Together, these studies show that NDIR technology is moving beyond lab proof-of-concept and into practical field-ready platforms (Sloan *et al.*, 2025; Verma *et al.*, 2026; Zeng *et al.*, 2026) ^[17, 18, 20].



Note: Created by the authors based on Dubey *et al.* (2024) ^[7], Sloan *et al.* (2025) ^[17], and Zeng *et al.* (2026) ^[20]

Fig 2: Working principle of an NDIR-based CO₂ sensor used for field monitoring

Digital and smart farming technologies

The real strength of intelligent monitoring lies not only in the sensor but in the digital system that surrounds it. IoT-based agriculture has made it possible to connect field sensors to wireless networks, microcontrollers, cloud databases, and mobile applications. Recent smart-agriculture systems have demonstrated real-time measurement of soil temperature, moisture, salinity, electrical conductivity, pH, and nutrient status, with AI-driven recommendation tools layered on top. Although these systems are not always designed specifically for CO₂, they create the infrastructure needed to interpret emission data alongside the soil and crop factors that influence respiration and carbon loss (Shahab *et al.*, 2025) ^[16].

In the context of carbon-sensitive farming, digital integration supports three major improvements. First, it allows multi-parameter interpretation, where a change in CO₂ can be read alongside irrigation, soil wetting, temperature change, or nutrient application. Second, it makes data storage and retrieval far easier, which helps build seasonal and multi-year datasets rather than scattered individual observations. Third, it enables alerts, dashboards, and recommendation systems that bring monitoring closer to management. This is especially useful for farms that may not have advanced research infrastructure but can still use low-cost sensors linked to phones or cloud platforms (Shahab *et al.*, 2025) ^[16].

Remote sensing also strengthens this digital transition. Gottschalk *et al.* (2024) ^[9] demonstrated that field-scale eddy covariance CO₂ fluxes can be combined with Sentinel-2 vegetation indices to estimate daily cropland carbon exchange at field scales. This is significant because it suggests that direct

field measurements and remotely sensed crop signals can be merged to improve spatial coverage and temporal continuity. For carbon-sensitive farming, such hybrid systems may allow future farms to combine local accuracy with whole-field or landscape-scale monitoring (Gottschalk *et al.*, 2024) ^[9].

Affordable CO₂ monitoring devices for field applications

Affordable CO₂ monitoring has become one of the most important research directions in this field because high instrument cost remains a major barrier to on-farm adoption and wider global use. Many conventional gas analyzers and commercial chamber systems are too expensive for repeated deployment across multiple plots, smallholder fields, teaching farms, or farmer-led monitoring networks. Recent work has responded directly to this limitation. Macagga *et al.* (2024) ^[14] developed a low-cost NDIR-based device for measuring CO₂ and evapotranspiration fluxes at about EUR 200 and validated it under field conditions, including hot and humid environments. Verma *et al.* (2026) ^[18] also developed a low-cost automated soil CO₂ flux chamber meant to support repeatable field measurements at much lower cost than commercial systems (Macagga *et al.*, 2024; Verma *et al.*, 2026) ^[14, 18].

The value of low-cost systems lies in both economics and design flexibility. When devices are cheaper, researchers and practitioners can deploy more units, increase replication, cover more of a field, and monitor for longer periods. This improves the chance of detecting spatial patterns and management-driven changes that single high-cost systems may miss. Low-cost devices also create new opportunities for farmer participation, extension work, and participatory science. That broadening of

access is a major advantage in carbon-sensitive farming because carbon awareness becomes more powerful when users can generate their own local evidence rather than relying on distant averages or generalized models (Sloan *et al.*, 2025) ^[17].

However, affordability only matters if the data are credible. Recent evaluations make clear that low-cost does not automatically mean low-quality, but it does require disciplined calibration and validation. Studies comparing low-cost sensors with reference instruments show that correction methods can dramatically improve performance. At the same time, long-term field evaluation studies show that drift can accumulate over months and years, meaning that carbon-sensitive systems need a maintenance plan, not just initial deployment. This is a critical message for practical farming systems: the instrument must be cheap enough to adopt, but the monitoring workflow must be robust enough to trust (Cai *et al.*, 2025; Dubey *et al.*, 2024) ^[6, 7]. Another design issue is chamber performance. Low-cost field chambers must manage mixing, reset time, sealing, and environmental interference. Verma *et al.* (2026) ^[18] and Zeng *et al.* (2026) ^[20] both addressed these design challenges by emphasizing repeatability, automated logging, and field operation details. These studies suggest that the future of affordable CO₂ monitoring will likely involve modular systems in which low-cost NDIR sensors are paired with better chamber mechanics, environmental correction algorithms, and data syncing tools (Verma *et al.*, 2026; Zeng *et al.*, 2026) ^[18, 20].

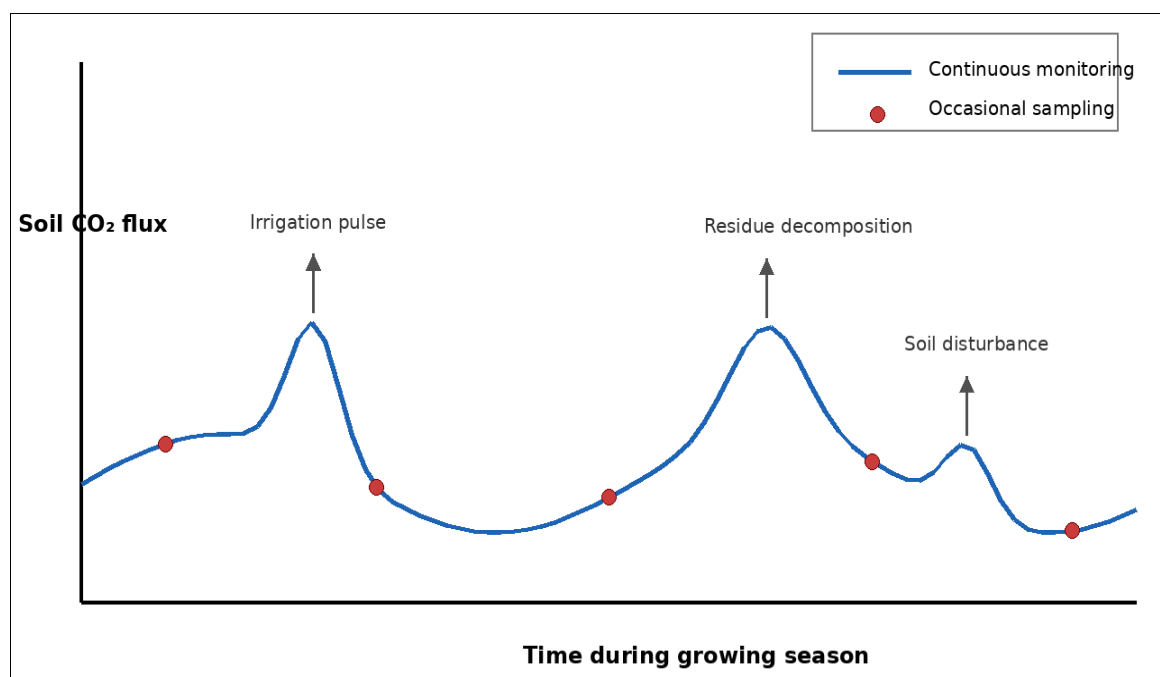
Role of continuous observation in emission monitoring

Continuous observation is one of the most important advances in intelligent emission monitoring because agricultural CO₂ fluxes are highly dynamic. Emissions respond to heat, moisture, vegetation growth, residue decomposition, tillage operations, and water pulses in ways that can change quickly over hours or

days. Studies on long-term and continuous monitoring systems have shown that a single reading or short campaign may miss major emission events or misrepresent average carbon behavior. This problem is especially serious in agriculture because management interventions often happen episodically but have lasting effects on soil carbon loss (Zeng *et al.*, 2026) ^[20].

Seasonal variation is especially important. Field studies in cropping systems show that soil temperature and moisture help drive emission changes across warm and cool periods, while crop growth and fallow dynamics alter the balance between respiration sources and carbon retention. Francioni *et al.* (2025) ^[8] demonstrated that fallow-period emissions in Mediterranean rotations can be meaningful and treatment-sensitive. Guarrera *et al.* (2024) ^[10] showed that orchard-scale CO₂ fluxes varied under different irrigation and mulching practices. These findings show why carbon-sensitive farming should be built on repeated observation across the year rather than only during peak crop growth (Francioni *et al.*, 2025; Guarrera *et al.*, 2024) ^[8, 10].

Continuous observation also produces better datasets for model development and decision support. Zeng *et al.* (2025) ^[19] showed that machine learning combined with hyperspectral imagery can be used to predict soil respiration in summer maize cropland, illustrating how frequent observations can support predictive environmental informatics. Bista *et al.* (2025) ^[3] likewise evaluated machine learning models for greenhouse gas emissions prediction in diversified semi-arid cropping systems using field-based measurements, showing the importance of site-specific data. These developments suggest that future carbon-sensitive systems will increasingly use continuous field measurements not only for direct interpretation but also to train predictive tools that extend monitoring into unmeasured periods and spaces (Bista *et al.*, 2025; Zeng *et al.*, 2025) ^[3, 19].



Note: Created by the authors based on Bista *et al.* (2025) ^[3], Zeng *et al.* (2025) ^[19], and Zeng *et al.* (2026) ^[20]

Fig 3: Illustrative comparison of continuous monitoring and occasional sampling for agricultural CO₂ emissions

Emission patterns and environmental data collection

Field emissions are not uniform. They vary across crop rows, mulched versus bare areas, wetter versus drier microsites, and disturbed versus undisturbed soil. Orchard experiments, long-term tillage trials, and portable sensor deployments all show that

small-scale variation matters. Guarrera *et al.* (2024) ^[10] reported that soil CO₂ fluxes in an orange orchard differed under different soil management and irrigation strategies. Similar logic appears in other field studies where tillage systems, fallow weed cover, or moisture regimes altered local emission patterns. Carbon-

sensitive farming therefore depends on environmental data collection that is both spatially aware and temporally rich (Guarrera *et al.*, 2024) ^[10]. The quality of such data depends on calibration, deployment consistency, and contextual environmental measurement. A CO₂ value without temperature, moisture, irrigation timing, or management context is much harder to interpret. That is why recent smart-agriculture platforms increasingly integrate multiple sensors and data streams. When a field monitoring system records CO₂ together with soil conditions and crop information, it becomes far easier to distinguish whether a flux increase reflects warming, irrigation-triggered microbial activity, residue mineralization, or some combination of these processes (Shahab *et al.*, 2025) ^[16]. Farmer and researcher participation in data collection is another major theme. Low-cost NDIR tools and citizen-science-oriented designs lower the barrier to involvement, making it possible for environmental monitoring to move beyond specialized laboratories. Sloan *et al.* (2025) ^[17] explicitly developed agricultural CO₂ monitoring systems for citizen scientists, which is important because carbon-sensitive farming will scale more effectively if local users can participate in measurement rather than only receiving external recommendations. Wider participation also increases awareness of climate and air quality issues and can strengthen local support for low-carbon practices (Sloan *et al.*, 2025) ^[17].

Farm management decisions based on monitoring data

The practical value of monitoring lies in decision-making. A carbon-sensitive farm does not collect data simply to document emissions; it uses those data to reduce avoidable losses and improve efficiency. Monitoring can inform decisions about tillage intensity, irrigation scheduling, residue handling, manure use, crop cover, and nutrient management. Recent studies show that such decisions have measurable consequences. In silage maize, frequent irrigation under manure fertilization increased cumulative emissions per area but lowered emissions per unit yield by supporting higher productivity, illustrating that management decisions should consider both area-based and yield-based carbon metrics (Aboubacar Dan Badaou & Sahin, 2025) ^[1]. Field evidence also shows that the same intervention can have different effects depending on context. In the Mediterranean fallow study by Francioni *et al.* (2025) ^[8], no-tillage did not always reduce emissions uniformly; treatment effects interacted with temperature, water status, and vegetation cover. In the Hungarian long-term tillage experiment, researchers examined how different tillage systems influenced soil biological activity, soil chemistry, plant physiology, and yield. These results underline an important principle of carbon-sensitive farming: management should be evidence-based and site-specific, not assumed to be universally beneficial simply because it is labeled conservation-oriented (Bozóki *et al.*, 2025; Francioni *et al.*, 2025) ^[4, 8]. Monitoring also strengthens precision agriculture. Once field CO₂ data are linked with moisture, temperature, crop imagery, and yield information, they can help identify zones of persistent carbon loss or inefficient input use. Remote sensing can extend that insight from point measurements to field-scale carbon dynamics, while AI and machine learning can support interpretation and prediction. This creates the possibility of carbon-informed precision management in which farms target both productivity and carbon efficiency (Gottschalk *et al.*, 2024) ^[9].

Carbon-sensitive farming for reducing field-level CO₂ emissions

Reducing field-level CO₂ emissions requires combining monitoring with management interventions. The recent literature suggests several promising directions. Tillage reduction remains a central strategy, though its effects depend on climate, soil, season, and vegetation dynamics. Francioni *et al.* (2025) ^[8] showed that soil CO₂ emissions during fallow periods differed between conventional tillage and no-tillage. Bozóki *et al.* (2025) ^[4] examined six tillage methods in a long-term Hungarian experiment and linked tillage systems with CO₂ emissions, soil properties, and crop performance. These studies support the view that lower-disturbance systems can reduce unnecessary carbon loss in many conditions, but they also emphasize the need for local measurement rather than universal assumptions (Bozóki *et al.*, 2025; Francioni *et al.*, 2025) ^[4, 8]. Water management is another strong lever. Irrigation changes soil moisture, oxygen diffusion, microbial activity, and residue breakdown, all of which affect CO₂ release. Guarrera *et al.* (2024) ^[10] showed that orchard CO₂ fluxes differed under full irrigation and regulated deficit irrigation, as well as under mulched versus bare soils. Aboubacar Dan Badaou and Sahin (2025) ^[1] found that irrigation regime altered emissions per unit area, per unit water, and per unit yield in manure-fertilized silage maize. Kularathna *et al.* (2026) ^[11] also examined how different irrigation and nitrogen fertilization rates affect CO₂ emissions and cotton yields in Southeast Texas. Together these studies show that carbon-sensitive irrigation is not simply about using less water, but about matching water timing and amount to crop needs while avoiding avoidable carbon loss (Aboubacar Dan Badaou & Sahin, 2025; Guarrera *et al.*, 2024; Kularathna *et al.*, 2026) ^[1, 10, 11]. Nutrient and residue strategies also matter. Organic amendments can stimulate microbial respiration and increase CO₂ loss in the short term, yet they may also improve soil structure, productivity, or long-term carbon balance depending on how they are used. This means that carbon-sensitive farming should evaluate both direct emissions and broader efficiency outcomes. Recent systems-level work on precision, AI-assisted agriculture suggests that data-driven nutrient recommendations can reduce unnecessary inputs and improve sustainability. When CO₂ data are read together with soil nutrient and moisture data, farms are better positioned to identify practices that drive carbon loss without proportional agronomic benefit (Shahab *et al.*, 2025) ^[16]. In practical terms, carbon-sensitive farming is strongest when mitigation is built as a feedback loop. Sensors and monitoring identify where and when emissions rise. Management changes are applied. New data then test whether those changes worked. This cycle is more powerful than static carbon accounting because it supports learning at field level and makes low-carbon farming adaptive over time (Sloan *et al.*, 2025) ^[17].

Table 3: Carbon-sensitive farming strategies for lowering field-level CO₂ emissions

Strategy	Description	Impact on CO ₂ Emissions
No-tillage	Minimal soil disturbance	Reduces emissions
Residue retention	Leaving crop residues	Improves carbon storage
Precision irrigation	Controlled water use	Reduces emission spikes
Smart fertilization	Optimized nutrient use	Reduces indirect emissions
Mulching	Soil cover	Stabilizes temperature & moisture
Crop rotation	Diverse cropping systems	Enhances soil health

Note: Created by author based on Bozóki *et al.* (2025) ^[4], Lal (2020) ^[13], and Shahab *et al.* (2025) ^[16]

In practical terms, carbon-sensitive farming is strongest when mitigation is built as a feedback loop. Sensors and monitoring identify where and when emissions rise. Management changes are applied. New data then test whether those changes worked. This cycle is more powerful than static carbon accounting because it supports learning at field level and makes low-carbon farming adaptive over time (Sloan *et al.*, 2025) ^[17].

Social and environmental benefits of low-cost sensing tools

Low-cost sensing tools have benefits that go beyond direct emission reduction. One of the most important is broader participation in environmental monitoring. High-cost equipment tends to concentrate data generation in a small number of well-funded laboratories or projects. Affordable NDIR-based devices, portable chambers, and simple IoT systems allow participation by students, extension workers, farmer groups, and citizen scientists. Sloan *et al.* (2025) ^[17] explicitly framed their design for citizen scientists, showing how low-cost agricultural CO₂ monitoring can expand who produces environmental data (Sloan *et al.*, 2025) ^[17].

This broader participation can strengthen environmental awareness. When users measure CO₂ themselves, carbon loss becomes more visible and less abstract. Farmers can relate emissions to irrigation timing, tillage, bare soil, or residue management in their own fields. Communities can build local evidence about soil health, carbon trends, and air-quality-related issues. Educational institutions can use affordable systems to train students in climate-smart agriculture. These outcomes matter because the transition to sustainable farming depends not only on technology but on understanding and ownership (Sloan *et al.*, 2025) ^[17].

Accessible monitoring can also support research and policy. Larger numbers of low-cost devices create denser datasets, which may help close spatial gaps in regions that are underrepresented in climate and soil monitoring networks. This is especially valuable in settings where conventional research infrastructure is limited. Macagga *et al.* (2024) ^[14] emphasized that low-cost measurement systems can help reduce global data gaps in agroecosystems. From a policy standpoint, better local data can improve the design of extension advice, carbon programs, and sustainability incentives (Macagga *et al.*, 2024) ^[14].

Challenges and limitations

Despite rapid progress, important challenges remain. The first is accuracy. Low-cost CO₂ sensors are promising, but sensor bias, drift, environmental interference, and device-to-device variability remain significant. Recent evaluation studies show that low-cost sensors can approach useful performance when calibrated carefully, yet long-term deployment still requires correction for environmental change and repeated recalibration. Without these safeguards, low-cost networks may generate misleading estimates (Cai *et al.*, 2025; Dubey *et al.*, 2024) ^[6, 7].

The second challenge is chamber and system design. Chamber-based measurements depend on sealing quality, mixing, headspace dynamics, and correct flux calculation. Poor design can produce major errors even if the CO₂ sensor itself is functioning well. Recent low-cost system papers have worked to solve these problems, but practical farm deployment still faces issues such as condensation, dust exposure, power supply, reset time, and enclosure durability. These are not trivial concerns in agricultural fields where equipment may face long outdoor exposure and variable weather (Verma *et al.*, 2026; Zeng *et al.*, 2026) ^[18, 20].

The third challenge is data interpretation. CO₂ emissions are biologically and physically complex. A rise in flux may reflect productive root activity, unwanted soil carbon mineralization, irrigation-triggered microbial activity, or changing temperature rather than a single simple cause. For this reason, CO₂ data should rarely be interpreted alone. Multi-parameter sensing, management records, and seasonal context are essential. Intelligent tools help, but interpretation still requires agronomic and environmental understanding (Shahab *et al.*, 2025) ^[16].

The fourth challenge is adoption. Even a low-cost device requires technical confidence, time, maintenance, and some data-handling capacity. Farmers may be interested in climate-smart practices but still hesitate if tools appear fragile, difficult to calibrate, or hard to translate into action. This means successful carbon-sensitive farming will need extension support, simple workflows, user-friendly dashboards, and clear economic or agronomic value in addition to scientific credibility (Sloan *et al.*, 2025) ^[17].

Future prospects and research needs

The future of carbon-sensitive farming will likely depend on better integration across sensing, analytics, and management. On the sensing side, researchers are moving toward more robust, portable, and lower-cost NDIR systems that can support repeatable field observations. The recent work by Verma *et al.* (2026) ^[18] and Zeng *et al.* (2026) ^[19] suggests that automated and portable low-cost soil respiration systems are becoming more feasible for routine deployment (Verma *et al.*, 2026; Zeng *et al.*, 2026) ^[18, 20].

On the analytics side, machine learning is likely to play a larger role in both calibration and prediction. Dubey *et al.* (2024) ^[7] showed that machine-learning-based calibration can improve low-cost CO₂ sensor performance, while Zeng *et al.* (2025) ^[19] and Bista *et al.* (2025) ^[3] demonstrated how ML approaches can help predict soil respiration or greenhouse gas emissions from field data. This suggests a future in which raw sensor data are continuously cleaned, corrected, and interpreted by embedded algorithms rather than only by post-processing in research settings (Bista *et al.*, 2025; Dubey *et al.*, 2024; Zeng *et al.*, 2025) ^[3, 7, 19].

A second major direction is hybrid monitoring that links in situ sensing with remote sensing. Gottschalk *et al.* (2024) ^[9] showed the promise of combining field-scale eddy covariance data with Sentinel-2 imagery to estimate daily cropland carbon exchange. Similar approaches could eventually connect low-cost chamber or probe systems with satellite-based vegetation and soil signals, creating multi-scale carbon monitoring frameworks for farms and landscapes (Gottschalk *et al.*, 2024) ^[9].

A third need is wider field validation. Many recent studies are still proof-of-concept, system-development, or site-specific experiments. More work is needed across cropping systems, climates, soil types, and management regimes to determine which low-cost systems remain accurate over time, which correction methods are most reliable, and how field protocols should be standardized. Long-duration studies are especially important because drift and operational wear often appear only after months of deployment (Cai *et al.*, 2025) ^[6].

Finally, future progress will depend on translating monitoring into farm value. Farmers are more likely to adopt carbon-sensitive systems if the data help improve irrigation efficiency, nutrient timing, yield stability, or eligibility for sustainability programs. Research should therefore continue to link CO₂ monitoring not only to emission estimates but also to agronomic outcomes, resource-use efficiency, and practical management recommendations (Aboubacar Dan Badaou & Sahin, 2025) ^[11].

Conclusion

Carbon-sensitive farming offers a useful framework for responding to the climate challenge in agriculture because it connects carbon awareness directly to field management. Rather than treating emissions as a distant policy metric, it treats them as a measurable part of farm performance. This makes it possible to reduce unnecessary field-level CO₂ losses through better-informed decisions about tillage, irrigation, nutrient management, residue handling, and soil cover (Francioni *et al.*, 2025) [8].

Intelligent tools are central to this transition. Low-cost NDIR sensors, automated and portable chambers, IoT-based environmental monitoring systems, machine-learning correction methods, and remote-sensing-assisted carbon estimation are together reshaping what is possible in agricultural emission monitoring. Recent research shows that affordable systems can work under field conditions, but it also makes clear that calibration, drift correction, chamber design, and contextual data remain essential (Dubey *et al.*, 2024) [7].

The broader importance of these tools lies in access. When monitoring becomes affordable and practical, more farmers, researchers, students, and citizen scientists can participate in environmental data collection. This supports better local understanding of carbon dynamics, improves awareness of climate and air-quality issues, and can strengthen the evidence base for sustainable agriculture. Carbon-sensitive farming is therefore not only a technical agenda but also a participatory one (Sloan *et al.*, 2025) [17].

Overall, the integration of intelligent monitoring systems with carbon-sensitive farming practices provides a realistic pathway toward lower field-level CO₂ emissions, improved management efficiency, stronger environmental accountability, and more sustainable agricultural production systems (Gottschalk *et al.*, 2024) [9].

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