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A review on water use efficiency in different cropping systems

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Abstract

One of the most important issues that have become significant to agricultural productivity in the world is water scarcity (FAO, 2021; Rockstrom *et al.*, 2010) ^[10, 31]. The issue of sustainability in crop production, especially in changing climatic conditions, therefore requires the need to improve on water use efficiency (WUE) (Blum, 2009) ^[3, 4]. WUE which is the ratio of the yield of crops to the consumption of water in terms of evapotranspiration is quite different between crops grown in various systems (Howell, 2001) ^[23]. Intercropping, crop rotation, conservation agriculture, agroforestry practices and others have been reported to enhance WUE by enhancing resource exploitation and soil moisture (Lithourgidis *et al.*, 2011; Kassam *et al.*, 2009) ^[29, 32]. The review summarizes the new research results on WUE using different cropping systems and identifies the main agronomic practices and technological interventions that increase the water productivity. The research also establishes gaps in research and proposes future trends on enhancing WUE in agriculture.

Keywords: Water use efficiency, Cropping systems, Intercropping, Crop rotation, Irrigation management, Sustainable agriculture

1. Introduction

Water is a basic production factor in agriculture and it takes an almost 70 percent portion of total freshwater abstractions around the world (FAO, 2021) ^[10]. Nevertheless, with the rising scarcity of water caused by climate change and population growth coupled with intensive agricultural systems, proper management of water has become a priority (Falkenmark, 2013; Rockstrom *et al.*, 2010) ^[31]. The use of Water Efficiency (WUE) has emerged as a major measure of sustainable agricultural systems that is used to explain the extent to which water has been used effectively to generate crop yield (Blum, 2009) ^[3, 4]. It is usually defined as a ratio of economic yield to evapotranspiration (ET) (Howell, 2001) ^[23]. An increase in WUE implies the improved use of available water resources. Cropping systems are also important in determining WUE as it impacts soil moisture dynamics, crop water uptake and evapotranspiration patterns (Passioura, 2006; Jiang *et al.*, 2025) ^[25, 33]. As a result, the concept of WUE in the context of various cropping systems is crucial to enhancing productivity at the expense of the use of the water resources.

2. Concept of Water Use Efficiency (WUE)

Water use efficiency is a multi-dimensional concept and its application differs according to the level and context of application (Sinclair, 2012) ^[34]. The yield of the water utilized is referred to as Agronomic WUE whereas the yield of biomass is called physiological WUE. The Irrigation WUE particularly looks at how well the irrigation water applied is used to contribute towards crop yield (Howell, 2001) ^[23]. WUE is affected by several factors such as climatic conditions, soil characteristics, crop species and management practices (Hatfield & Dold, 2019; Wang *et al.*, 2024) ^[20, 35]. As an example, excessive temperature and low humidity may raise the rate of evapotranspiration, thus lowering the WUE (Monteith, 1977) ^[36]. On the same note, water

retention and availability to plants depends on soil texture and structure (Gregory *et al.*, 2000) ^[19]. Scheduling of irrigation and nutrient management are efficient management practices that may contribute greatly to the WUE (Fereses & Soriano, 2007; Wang *et al.*, 2024) ^[13, 35].

2.1 Variability in WUE of different crops

Water Use Efficiency (WUE) among crops differs greatly because of the physiological and biochemical differences inherent in crops, especially in their photosynthetic pathways. C₃-type crops (wheat, rice etc.) tend to have a lower WUE due to the fact that they are more susceptible to photorespiration, particularly in high temperature and low CO₂ conditions, resulting in higher loss of water per unit biomass produced (Blum, 2009; Long *et al.*, 2006) ^[3, 4]. By contrast, C₄ crops such as maize and sorghum are able to sequester carbon within a concentration mechanism that reduces photorespiration and maximizes the capability of fix carbon and thus higher WUE is attained with a given environment (Sage & Zhu, 2011; Ghannoum, 2009) ^[16, 37]. This inherent distinction has a direct connection to transpiration efficiency in which C₄ crops generate more biomass per unit water transpired than C₃ crops (Farquhar *et al.*, 1989) ^[12]. Though pulse crops are predominantly C₃ in nature, they show moderate WUE but work effectively in water-limited conditions because of their adaptive characteristics of deep rooting systems, osmotic adjustment and reduced water needs (Graham and Vance, 2003; Sinclair and Vadez, 2012) ^[17, 18, 34]. In this way, crop-specific WUE is highly regulated by photo-synthetic pathway and transpiration relationship, crop selection is a key factor in enhancing the overall water

productivity within various agro-ecological systems.

3. Water Use Efficiency under Different Cropping Systems

3.1 Monocropping Systems

Monocropping is the common practice that is characterized by growing one type of crop in the same soil, being grown at different periods. It is the easiest and simplest method of farming because it is easy to manage. Nevertheless, such a system may lead to reduced WUE because of unhealthy soils, excessive evaporation losses and inefficient use of resources (Tilman *et al.*, 2002; Lal, 2015) ^[38, 39]. In fact, an instance of continuous monocropping may cause degradation of soil, decrease in organic matter and decrease in root diversity which are disadvantaged in terms of water retention and uptake. Research has indicated that monocropping systems tend to have low WUE relative to diversified systems especially where water is a constraint.

3.2 Intercropping Systems

Intercropping is the concomitant planting of two or more crops within a single field and this has been well known to improve the WUE (Lithourgidis *et al.*, 2011) ^[32]. This system enhances the use of resources using disparity in depth of roots of crops, structure of canopy and the period of growth of crops (Tsubo & Walker, 2004) ^[41]. Consequently, intercropping minimizes the use of evaporation losses and enhances efficiency of utilizing soil moisture. Indicatively, intercropping systems, specifically maize soybean systems, have been reported to enhance WUE up to 40 percent over monocropping because it provides a better spatial and temporal utilization of resources (Sai *et al.*, 2024; Zhang *et al.*, 2018; Gao *et al.*, 2010) ^[42, 43].

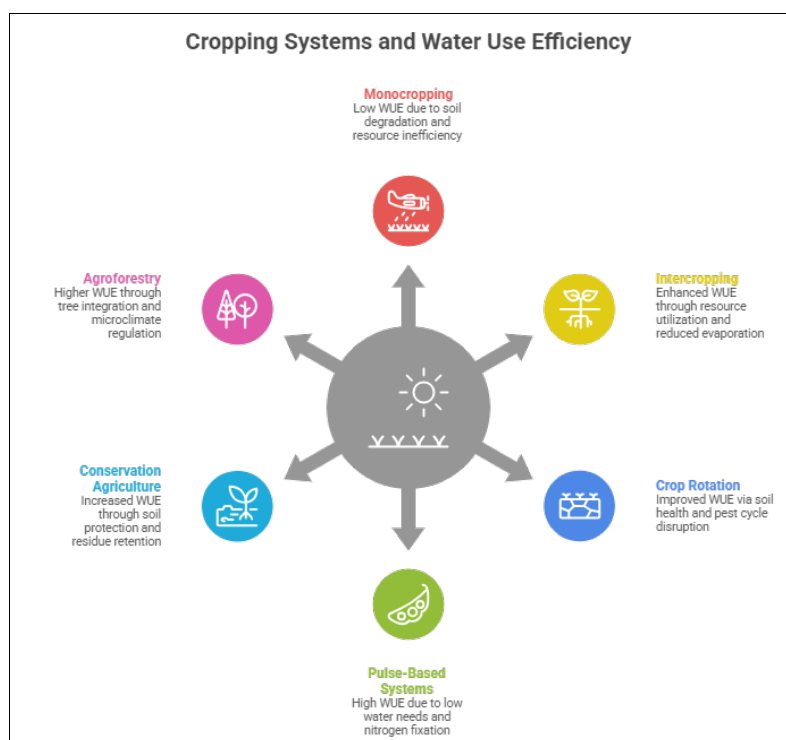


Fig 1: Cropping Systems and Water Use Efficiency

3.3 Crop Rotation Systems

Crop rotation: The sequential growth of other varieties of crops on the same land is important in enhancing the health of the soil and water efficiency (Karlen *et al.*, 1994) ^[28]. Rotation systems increase the soil structure, improve organic compounds and water absorption and retention (Hobbs *et al.*, 2008) ^[22]. These transformations lead to the use of water more efficiently. An

example is the use of wheat-maize rotation systems, which are found to increase the WUE over that of continuous monocropping systems by 12-32 percent. Crop rotation also contributes to the breaking of the pest and disease cycles reducing stress on crops and enhancing the overall productivity and water use.

3.4 Pulse-Based Cropping Systems

Pulse crops can fix nitrogen in the atmosphere and have a low water demand hence they have great significance in sustainable agriculture (Graham & Vance, 2003) [17, 18]. Pulses in the systems enhance the structure of the soil and the rate of water penetration and thus increase the WUE (Peoples *et al.*, 2009) [45]. Pulse-based systems are most useful in rainfed and water scarce areas. Researches have revealed the incorporation of pulses with cereals can greatly enhance the WUE by enhancing nutrient and water use effectiveness (Thakur *et al.*, 2025) [46].

3.5 Conservation Agriculture Systems

Conservation agriculture (CA), such as zero tillage, residue retention and crop diversification, have been popularly advanced with regard to enhancing WUE (Kassam *et al.*, 2009) [29]. The practices minimize soil disturbance, increase soil organic content and raise the water percolation and absorption (Farooq *et al.*, 2011) [11]. The retention of the residues in the soil surface decreases the loss of evaporation and the soil is kept moist (Unger, 1990) [47]. Consequently, CA systems tend to be more WUE than traditional tillage systems are (Wang *et al.*, 2024) [35].

3.6 Agroforestry Systems

Agroforestry systems integrate trees with crops, creating a more diverse and resilient production system (Nair, 2012) [48]. Trees play a crucial role in improving soil structure, enhancing water infiltration and reducing evaporation through shading (Jose, 2009) [27]. Deep-rooted trees can access water from deeper soil layers, making it available to crops indirectly (Wallace, 2000) [49]. This complementary use of water resources leads to higher overall WUE in agroforestry systems compared to sole cropping.

Table 1: Comparison of Water Use Efficiency under Different Cropping Systems

Cropping System	Key Features	Effect on WUE	Reason for Change in WUE
Monocropping	Single crop grown repeatedly	Low	Poor soil health, high evaporation losses
Intercropping	Two or more crops grown together	High	Complementary root use, reduced evaporation
Crop Rotation	Sequential cropping of different crops	Moderate-High	Improved soil structure and moisture retention
Pulse-based System	Inclusion of legumes	High	Nitrogen fixation, better soil aggregation
Conservation Agriculture	Zero tillage + residue retention	Very High	Reduced evaporation, improved soil moisture
Agroforestry	Integration of trees and crops	High	Deep root systems and microclimate regulation

3.7 Climate Change and Water Use Efficiency

Climate change can affect water use efficiency greatly by changing rainfall patterns, rising temperature and enhancing evapotranspiration losses. Increasing temperatures enhance the demand of water by crops and unpredictable precipitation decreases the water supply, thus worsening the WUE (IPCC, 2021; Hatfield and Prueger, 2015) [21, 24]. The presence of extreme weather conditions like droughts and heatwaves also worsen the situation of water stress and cause low crop productivity. The absence of adaptation mechanisms to mitigate the impact of climatic changes on WUE, including climate-resilient cropping systems, drought-tolerant varieties and better irrigation timing, is necessary to maintain WUE (Leng and Hall,

2019; Zhao *et al.*, 2017) [50, 51]. In addition, the incorporation of weather-based decision support systems can assist farmers in optimizing their irrigation and cropping schedule to enhance water productivity in the climate variability (Raza *et al.*, 2019) [52].

3.8 Soil Health and Microbial Interactions in Enhancing WUE

The health of the soil is an important factor in setting the efficiency of water use, directly influencing the water retention, infiltration, root development. Well-nourished soils full of organic elements also enhance water retention and minimize run-off wastage (Lal, 2020) [40]. Plant water uptake is promoted by soil microbial communities, such as mycorrhizae and plant growth-promoting rhizobacteria (PGPR), which increase root architecture and nutrient availability (Smith and Smith, 2011; Vurukonda *et al.*, 2016) [53, 54]. Such beneficial microbes are also useful in enabling plants to endure drought stress by controlling physiological functions. Organic amendments, cover cropping and reduced tillage are some of the practices that increase soil biological activity and consequently, WUE (Bender *et al.*, 2016; six *et al.*, 2004) [2, 55]. Therefore, preserving soil health is an important approach to enhancing water productivity in agriculture.

3.9 Policy and Socio-economic Aspects of Water Use Efficiency

Policy support and socio-economic conditions have a strong impact on the adoption of water-efficient technologies and cropping systems. Smallholder farmers in most developing countries are hampered by lack of irrigation infrastructure, financial resources and technical expertise (Shiferaw *et al.*, 2014) [56]. The policies of the government that encourage micro-irrigation, water pricing and subsidies of efficient technologies can also be of great help in improving WUE on a farm level (Rosegrant *et al.*, 2009) [57]. Other promising solutions to enhance water distribution efficiency include community-based water management and participatory irrigation systems (Meinzen-Dick, 2007) [58]. Moreover, the extension services and capacity building are very vital in sharing the knowledge on water saving practices and technologies (Pretty *et al.*, 2018) [59]. Thus, to enhance WUE, it is necessary, not just to undertake technological interventions but also to have robust institutional and policy frameworks.

4. Agronomic Practices Influencing WUE

There are a number of agronomic practices that have a profound impact on efficiency of water resources in crop systems. The effective irrigation practices like drip irrigation and sprinkler irrigation apply water in the root zone which minimizes the loss through evaporation and water run-off (Fereres & Soriano, 2007; Pereira *et al.*, 2012) [13, 60]. The techniques have been cited to enhance the WUE by 10-18 percent over the traditional flood irrigation. Another practice that is significant and enhances WUE is mulching, which lessens soil evaporation, retains moisture and improves soil temperature (Farooq *et al.*, 2011) [11]. The choice of suitable crop varieties, especially the drought tolerant and short life cycle varieties are also important in enhancing the water productivity (Blum, 2011) [5]. Also, the balanced management of nutrients helps to achieve superior root growth and water uptake, which lead to increased WUE (López-Bellido *et al.*, 2005; Wang *et al.*, 2024) [35, 63].

Table 2: Agronomic Practices Influencing Water Use Efficiency

Practice	Description	Impact on WUE (%)	Mechanism
Drip Irrigation	Water applied directly to root zone	+10-18%	Reduces evaporation and runoff
Sprinkler Irrigation	Uniform water distribution	+8-15%	Efficient water application
Mulching	Covering soil with organic/inorganic material	+15-25%	Reduces evaporation, conserves moisture
Deficit Irrigation	Controlled water stress	+5-20%	Optimizes water use without yield loss
Balanced Fertilization	Proper nutrient supply	+10-15%	Enhances root growth and uptake
Improved Varieties	Drought-tolerant cultivars	+10-30%	Better water extraction efficiency

5. Role of Modern Technologies in Improving WUE

The technological progress has provided new opportunities to enhance the efficiency of water use in agriculture. Monitoring water status and evapotranspiration of crops can be accurately conducted with the help of remote sensing and geographic information system (GIS) (Jones, 2004; Zhang *et al.*, 2002)^[26, 44]. Automated irrigation systems and soil moisture sensors can be used to optimize the timing of irrigation so that crops get the appropriate quantity and timing of water. There is an increasing use of artificial intelligence (AI) and decision support systems (DSS) to enhance the management of water (Zwart & Bastiaanssen, 2004; Wang *et al.*, 2024)^[35, 61]. These technologies promote the efficiency of water utilization on a field and regional basis.

Table 3: Water Use Efficiency in Major Cropping Systems

Cropping System	Region/Condition	WUE Improvement (%)	Reference
Maize + Soybean	Semi-arid regions	Up to 40%	Sai <i>et al.</i> (2024) ^[42]
Wheat-Maize Rotation	Irrigated systems	12-32%	
Pulse-based systems	Rainfed regions	15-25%	Thakur <i>et al.</i> (2025) ^[46]
Conservation Agriculture	Dryland agriculture	20-50%	Wang <i>et al.</i> (2024) ^[35]
Agroforestry systems	Tropical regions	15-35%	Zhang <i>et al.</i> (2018) ^[43]

6. Research Gaps and Future Prospects

In spite of the major progress, there are still a number of research gaps associated with the field of water use efficiency. Long term research is required to determine the viability of various cropping systems to diverse climatic conditions (Pretty *et al.*, 2018)^[59]. There are no region-specific recommendations that can be given especially to the small holder farmers in the developing world (Sharma *et al.*, 2015)^[62]. Moreover, there is a lack of employment of water-saving technologies because of the economic and infrastructural factors. Future studies must consider combining climate-smart agricultural methods with the use of modern technologies in order to improve WUE (Kijne *et al.*, 2003)^[30].

7. Conclusion

Efficiency of water use is an important aspect in realization of

sustainable agricultural production as water scarcity increases. Various systems of cropping intercropping, crop rotation, conservation agriculture and agroforestry have revealed a great potential of enhancing WUE as opposed to monocropping systems (Lithourgidis *et al.*, 2011; Kassam *et al.*, 2009)^[29, 32]. Water productivity can be further increased by adoption of better agronomic practices and modern technologies. The effective use of water in agriculture needs to be holistic and should be a mixture of an efficient cropping system, technological advances and policy support.

References

- Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO; 1998.
- Bender SF, Wagg C, van der Heijden MGA. An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. Trends in Ecology & Evolution. 2016;31(6):440-452.
- Blum A. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Research. 2009;112(2-3):119-123.
- Blum A. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Research. 2009;112(2-3):119-123.
- Blum A. Plant breeding for water-limited environments. Springer; 2011.
- Bouman BAM. A conceptual framework for the improvement of crop water productivity at different spatial scales. Agricultural Systems. 2007;93(1-3):43-60.
- Chaves MM, Maroco JP, Pereira JS. Understanding plant responses to drought from genes to the whole plant. Functional Plant Biology. 2003;30(3):239-264.
- Connor DJ, Loomis RS, Cassman KG. Crop ecology: Productivity and management in agricultural systems. 2nd ed. Cambridge University Press; 2011.
- Falkenmark M. Growing water scarcity in agriculture: Future challenge to global water security. Philosophical Transactions of the Royal Society A. 2013;371(2002):20120410.
- FAO. The state of the world's land and water resources for food and agriculture. Food and Agriculture Organization; 2021.
- Farooq M, Flower KC, Jabran K, Wahid A, Siddique KH. Crop yield and weed management in conservation agriculture. Soil and Tillage Research. 2011;117:172-183.
- Farquhar GD, Ehleringer JR, Hubick KT. Carbon isotope discrimination and photosynthesis. Annual Review of Plant Biology. 1989;40:503-537.
- Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany. 2007;58(2):147-159.
- Gao Y, Duan A, Qiu X, Liu Z, Sun J, Zhang J, Wang H. Distribution of roots and root length density in a maize/soybean strip intercropping system. Field Crops Research. 2010;120(2):236-245.
- Geerts S, Raes D. Deficit irrigation as an on-farm strategy to maximize crop water productivity. Agricultural Water Management. 2009;96(9):1275-1284.
- Ghannoum O. C4 photosynthesis and water stress. Annals of Botany. 2009;103(4):635-644.
- Graham PH, Vance CP. Legumes: Importance and

- constraints to greater use. *Plant Physiology*. 2003;131(3):872-877.
18. Graham PH, Vance CP. Legumes: Importance and constraints to greater use. *Plant Physiology*. 2003;131(3):872-877.
 19. Gregory PJ, Simmonds LP, Pilbeam CJ. Soil type, climatic conditions and root system interactions. *Plant and Soil*. 2000;225:199-215.
 20. Hatfield JL, Dold C. Water-use efficiency: Advances and challenges. *Agronomy Journal*. 2019;111(6):2561-2573.
 21. Hatfield JL, Prueger JH. Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*. 2015;10:4-10.
 22. Hobbs PR, Sayre K, Gupta R. The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B*. 2008;363:543-555.
 23. Howell TA. Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*. 2001;93(2):281-289.
 24. IPCC. *Climate Change 2021: The Physical Science Basis*. Cambridge University Press; 2021.
 25. Jiang Y, Wang X, Liu H, Zhang Y. Cropping systems and water use efficiency under climate change. *Agricultural Water Management*. 2025;280:108205.
 26. Jones HG. Irrigation scheduling: Advantages and pitfalls of plant-based methods. *Journal of Experimental Botany*. 2004;55(407):2427-2436.
 27. Jose S. Agroforestry for ecosystem services and environmental benefits. *Agroforestry Systems*. 2009;76(1):1-10.
 28. Karlen DL, Varvel GE, Bullock DG, Cruse RM. Crop rotations for the 21st century. *Advances in Agronomy*. 1994;53:1-45.
 29. Kassam A, Friedrich T, Shaxson F, Pretty J. The spread of conservation agriculture. *International Journal of Agricultural Sustainability*. 2009;7(4):292-320.
 30. Kijne JW, Barker R, Molden D. *Water productivity in agriculture: Limits and opportunities*. CABI; 2003.
 31. Rockstrom J. Planetary boundaries. *New Persp. Q.*. 2010;27:72.
 32. Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios DO. Annual intercrops: an alternative pathway for sustainable agriculture. *Australian journal of crop science*. 2011 Apr 1;5(4):396-410.
 33. Passioura J. Increasing crop productivity when water is scarce from breeding to field management. *Agricultural water management*. 2006 Feb 24;80(1-3):176-96.
 34. Sinclair B. *The social citizen: Peer networks and political behavior*. University of Chicago Press; 2012 Dec 10.
 35. Wang W, Lv Q, Yu W, Hong W, Qi J, Wang Y, Ji J, Yang Z, Zhao L, Song X, Xu J. Cogvlm: Visual expert for pretrained language models. *Advances in Neural Information Processing Systems*. 2024 Dec 16;37:121475-99.
 36. Monteith JL. Climate and the efficiency of crop production in Britain. *Philosophical transactions of the royal society of London. B, Biological Sciences*. 1977 Nov 25;281(980):277-94.
 37. Sage RF, Zhu XG. Exploiting the engine of C4 photosynthesis. *Journal of experimental botany*. 2011 May 1;62(9):2989-3000.
 38. Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S. Agricultural sustainability and intensive production practices. *Nature*. 2002 Aug 8;418(6898):671-7.
 39. Lal R. Restoring soil quality to mitigate soil degradation. *Sustainability*. 2015 May 13;7(5):5875-95.
 40. Lal R. Regenerative agriculture for food and climate. *Journal of soil and water conservation*. 2020 Sep 1;75(5):123A-4A.
 41. Tsubo M, Walker S. Shade effects on *Phaseolus vulgaris* L. intercropped with *Zea mays* L. under well-watered conditions. *Journal of Agronomy and Crop Science*. 2004 Jun;190(3):168-76.
 42. Sai JM, Priyadarshini GI, Goud GP, Varma DH, Pitchai R, Jyothirmai D. Smart and sustainable framework for maize leaf disease prediction using deep learning techniques. In *2024 First International Conference on Technological Innovations and Advance Computing (TIACOMP) 2024 Jun 29 (pp. 467-471)*. IEEE.
 43. Zhang X, Zhou X, Lin M, Sun J. Shufflenet: An extremely efficient convolutional neural network for mobile devices. In *Proceedings of the IEEE conference on computer vision and pattern recognition 2018 (pp. 6848-6856)*.
 44. Zhang K, Calabrese P, Nordborg M, Sun F. Haplotype block structure and its applications to association studies: power and study designs. *The American Journal of Human Genetics*. 2002 Dec 1;71(6):1386-94.
 45. Peoples M^A, Brockwell J, Herridge DF, Rochester IJ, Alves BJ, Urquiaga S, Boddey RM, Dakora FD, Bhattarai S, Maskey SL, Sampet C. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*. 2009 Feb;48(1):1-7.
 46. Thakur TK, Patel DK, Thakur A, Arora NK. Evaluation of land degradation vulnerability in coal mined areas of Madhya Pradesh, India using geospatial and AHP modeling: a 40-year assessment and eco-restoration of degraded landscape. *Environmental Sustainability*. 2025 Mar;8(1):85-101.
 47. Unger P. *Identity, consciousness and value*. Oxford University Press; 1990 Jul 12.
 48. Nair PK. Carbon sequestration studies in agroforestry systems: a reality-check. *Agroforestry systems*. 2012 Oct;86(2):243-53.
 49. Wallace JM. North Atlantic oscillation annular mode: two paradigms one phenomenon. *Quarterly Journal of the Royal Meteorological Society*. 2000 Apr;126(564):791-805.
 50. Leng G, Hall J. Crop yield sensitivity of global major agricultural countries to droughts and the projected changes in the future. *Science of the Total Environment*. 2019 Mar 1;654:811-21.
 51. Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P, Durand JL. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of sciences*. 2017 Aug 29;114(35):9326-31.
 52. Raza A, Razzaq A, Mehmood SS, Zou X, Zhang X, Lv Y, Xu J. Impact of climate change on crops adaptation and strategies to tackle its outcome: A review. *Plants*. 2019 Jan 30;8(2):34.
 53. Smith SE, Jakobsen I, Grønlund M, Smith FA. Roles of arbuscular mycorrhizas in plant phosphorus nutrition: interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. *Plant physiology*. 2011 Jul 1;156(3):1050-7.
 54. Vurukonda SS, Vardharajula S, Shrivastava M, SkZ A. Enhancement of drought stress tolerance in crops by plant growth promoting rhizobacteria. *Microbiological research*. 2016 Mar 1;184:13-24.

55. Six J, Bossuyt H, Degryze S, Denef K. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and tillage research*. 2004 Sep 1;79(1):7-31.
56. Shiferaw B, Tesfaye K, Kassie M, Abate T, Prasanna BM, Menkir A. Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and climate extremes*. 2014 Jun 1;3:67-79.
57. Rosegrant MW, Ringler C, Zhu T. Water for agriculture: maintaining food security under growing scarcity. *Annual review of Environment and resources*. 2009 Nov 21;34:205-22.
58. Meinzen-Dick R. Beyond panaceas in water institutions. *Proceedings of the national Academy of sciences*. 2007 Sep 25;104(39):15200-5.
59. Pretty J, Benton TG, Bharucha ZP, Dicks LV, Flora CB, Godfray HC, Goulson D, Hartley S, Lampkin N, Morris C, Pierzynski G. Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability*. 2018 Aug;1(8):441-6.
60. Pereira HM, Navarro LM, Martins IS. Global biodiversity change: the bad, the good, and the unknown. *Annual review of environment and resources*. 2012 Nov 21;37:25-50.
61. Zwart SJ, Bastiaanssen WG. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural water management*. 2004 Sep 15;69(2):115-33.
62. Sharma VK, Filip J, Zboril R, Varma RS. Natural inorganic nanoparticles-formation, fate, and toxicity in the environment. *Chemical Society Reviews*. 2015;44(23):8410-23.
63. López-Bellido L, López-Bellido RJ, Redondo R. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. *Field crops research*. 2005 Oct 14;94(1):86-97.