

ENHANCING AGRICULTURAL WATER PRODUCTIVITY OF CROPS AT FIELD SCALE

Abstract

In order to achieve enhanced water management for sustainable agriculture, food security, and healthy functioning of ecosystem, water productivity must be increased. Agricultural water productivity is the agricultural output, in physical or monetary terms, generated per unit of water consumed or applied. Plants take up water primarily from soil. Thus, judicious water management in field starts with real-time assessment of soil moisture content *viain-situ* or remote sensing-based methods. This chapter reviews opportunities for improving field-scale water productivity by the use of precision agronomic and water management technologies. In field scale, water productivity, or water use efficiency of crops, can be improved by seed priming, maintaining proper row-direction of crops, following prudent nutrient management practices to harness synergy of water-nutrient interaction, minimizing water application *via* drip and sprinkler irrigation or optimizing the same *via* precision irrigation approaches, reducing unproductive water losses through conservation agricultural practices or application of antitranspirants, and increasing the water retention capacity of soils by applying soil conditioners *etc.* Identifying the most promising combination of options for improving water productivity is complex and largely determined by the economic capacity of the stakeholders.

Keywords: Antitranspirants (AT); Agricultural water productivity (AWP)

Authors

Debasish Roy

Division of Agricultural Physics
ICAR- Indian Agricultural
Research Institute
New Delhi, India
roydeba93@gmail.com

Tridiv Ghosh

Division of Agricultural Physics
ICAR- Indian Agricultural
Research Institute
New Delhi, India

Arkaprava Roy

Division of Soil Science and Agricultural
Chemistry ICAR- Indian Agricultural
Research Institute New Delhi, India

Mithu Gogoi

Department of Soil Science and
Agricultural Chemistry
Uttar Banga Krishi Viswavidyalaya
West Bengal, India

Khurshid Alam

Division of Soil Science and
Agricultural Chemistry
ICAR- Indian Agricultural
Research Institute
New Delhi, India

Raktim Mitra

Division of Plant Physiology
ICAR- Indian Agricultural
Research Institute
New Delhi, India

I. INTRODUCTION

Agricultural water productivity (AWP) signifies the benefit obtained from crop production in expense of water resources utilized to fetch those benefits. The effort should be consolidated to generate more farm income in expense of per unit of water used, for attaining secure daily livelihood and environmental benefits. In conventional crop physiological perspective, agricultural water use efficiency is defined as the total quantity of biomass or marketable output produced per unit of water used for either transpiration or evapotranspiration [1]. However, irrigation engineers defined the same as the relative proportion of irrigation water transpired by standing crops in any irrigation unit or command area during crop growth period [2]. However, both these definitions are silent about economic benefit and efficiency of water application through field scale irrigation. AWP includes the perspective to grow more food, fetch higher farm income, and sustain livelihood security and support ecological benefit at far less social and environmental cost per unit of water consumed [3];[4]; [5]. There are three different perspectives for defining AWP which are as follows:

Table 1: Types of Agricultural Water Productivity

SL no.	Types of AWP	Definitions	Units
1.	Physical water productivity (PWP)	Crop output / Amount of water consumed	kg m ⁻³
2.	Irrigation water productivity (IWP)	Crop output / Amount of irrigation water applied	kg m ⁻³
3.	Economic water productivity (EWP)	Value earned after selling crop output / Amount of water consumed (or irrigation water applied)	Rs. m ⁻³

AWP is most preferably expressed in terms of either depleted water from soil profile during the entire Plant Growth Period (PWP) or the net amount supplied water (IWP; *via* surface canals, tank, pond or the well and tube well) to grow crop. For high water demanding crops (*viz.* Rice, Wheat and Sugarcane) PWP fails to present the actual field condition as farmers apply excess amount of irrigation water than the actual crop requirement. The external source of water supplementation through irrigation often includes the contribution from the seasonal rainfall as ‘green’ water and applied irrigation water *i.e.* ‘blue’ water (from natural or artificial water systems); evapotranspiration (ET) bears a major contribution for the profile moisture depletion for determining the agricultural water productivity during the crop growth period. It takes into account the contribution of surface run off and limited reuse of polluted water generated within the crop production system [6]. Globally, more than 70% of total water are used for irrigation that covers more than 90% of total consumptive water use [7] ; [8]. To sustain our water safety and food security, the wider adaptation of ‘more crop per drop’ approach for increasing the AWP is an inevitable option [9];[10]; [11] and, at the same time, critical for bringing economic development in the arid and semi-arid regions of India [12]. Proper dissemination of the social benefits of higher AWP will encourage the adaptation of process-based AWP simulations for investigating and predicting system-crop-productivity

under variable irrigation management practices in diverse agro-ecosystem models [13]. Agronomic measures and efficient management of irrigation water has the potential to increase land productivity as well as the water productivity of agro-ecosystems in many developing countries. The fundamental approach are mostly relied on either increase in crop productivity with stabilized net crop water use or securing stabilized yield with limited or reduced (conjunctive use) crop water use. In this chapter, we discuss some solutions for improving AWP which could be feasible for the farmers of developing countries like India.

II. Approaches for Real Time Soil Moisture Monitoring

Soil moisture (SM) is an important factor in irrigation schedule. Because of the complexity of SM, exact and real-time measurement is difficult. The soil texture, irrigation, and climatic conditions all have an impact on the vertical profile of SM readings, which is extremely complicated and changes greatly with depth.. Increasing the demand per unit of water, especially the opportunities for employment, income generation and nutrition; for that near real time soil moisture monitor need to be done for water productivity analysis.

1. Gravimetric method: The gravimetric method is the simplest and most widely used one for the determination of soil water content. By using an auger or another sampling instruments, soil samples are taken from the field, put in aluminium cans, and sealed to stop moisture loss while being transported to the lab. The moisture samples are first weighed and then dried to a constant weight in an oven at 105 to 110°C. The difference between moist and dry weight gives the water content in the soil samples. In general, the water content is expressed as percentage of dry weight of the soil. For irrigation purposes it is much more useful to express the water content on a volume basis. The volumetric water content θ , are calculated by the following equation:

$$\theta = \frac{\rho}{\rho_w} \times \theta_w \quad (1)$$

Where, ρ_w = density of water g.cm^{-3} ; ρ = bulk density of the soil samples, g.cm^{-3}

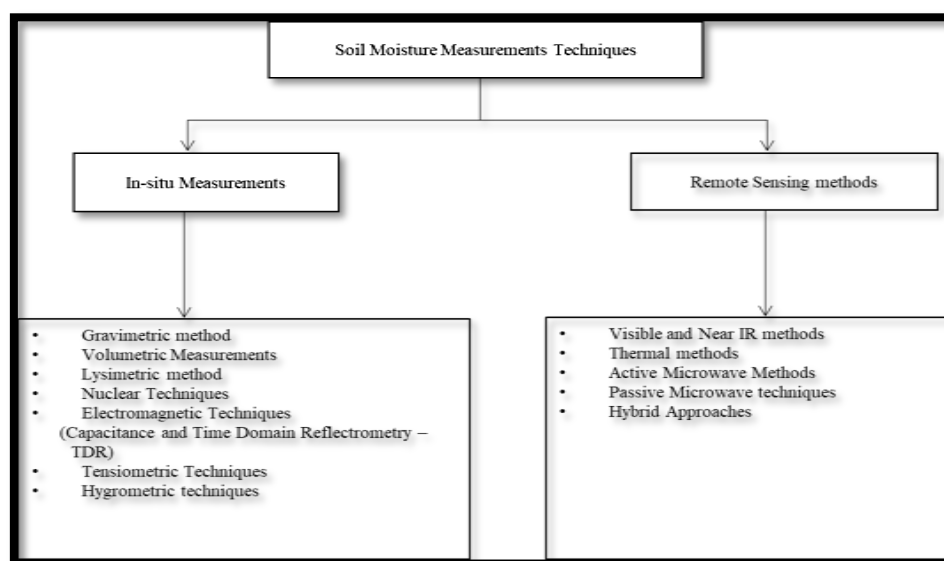


Figure 1: Soil Moisture Measurement Techniques

2. **Lysimetric method:** Lysimeter have been used for long time for evaluating agricultural hydrology. By the use of weighing Lysimeters it is possible to measure the water content continuously in the same mass of soil without destructive sampling. Lysimeter are accurate and commonly used for evapotranspiration measurements.
3. **Nuclear techniques:** Among the recent advancement of nuclear techniques for soil moisture estimation, which are non-destructive in nature, two methods have been used with success, one is neutron scattering method and another is gamma radiation method. In the former, the amount of water by volume is determined by counting the number of hydrogen nuclei present per unit volume of soil. The attenuation of a broad, near parallel beam of gamma radiation is used to characterize the water status of soil. This method has been successfully used in the laboratory to make continuous measurements of the water content of soil layers in fixed columns.
4. **Electromagnetic techniques:** Since the late 1980s, technical advancements have increased the reliability of SM measurements, especially the dielectric methods. The ability to measure SM on a commercial scale using a variety of electromagnetic (EM) methods has gained popularity due to their cheaper cost and simplified training requirements. The electrical signal response of the EM sensors is used to monitor SM. Sensors are commonly made up of plastic access tubes that are put vertically into the soil to measure the moisture level. The dielectric constant of the soil components affects the frequency signals that the capacitance sensors use to function. Capacitance and time domain reflectometry (TDR) are two sensors that are commonly employed for SM monitoring.
5. **Precision Agriculture techniques to enhance agricultural water productivity**

The major interventions that can substantially increase the AWP are discussed below:

- **Priming:** Priming is the technique of supplying a small amount of water to complement the first phase of germination. Seed priming has been practised for centuries, with reported growth benefits for a range of crops. To improve seed viability and performance in the field, a variety of priming procedures have been used. In order to reduce the quantity of water needed for the germination process, advancing is a simple process that entails imbibing with a little amount of water. Carrot seed germination rates have been observed to increase by 2-3% after advancing, according to the observation.[14]; [15]. Hydropriming is the process of partially hydrating (10-20 % of complete) seed with distilled water to improve its tolerance to salinity or drought[16]; [17]. Osmo-priming employs osmotic solutions to reduce oxidative damage, which lessens the impact of reactive oxygen species.[18]; [19]. As a result, priming has various advantages, particularly in stressful situations.[20]; [17]; [21]. Primed seeds are rapidly dehydrated before storage to return the moisture content to its original level [22].
- **Row direction:** Plant geometry influences crop productivity through influencing Intercepted Photosynthetically Active Radiation (IPAR), biomass production, Leaf

Area Index (LAI), profile soil moisture storage, radiation use efficiency (RUE), water usage efficiency (WUE), and so on. Water scarcity is one of the major abiotic stresses impacting agriculturally important crops growth, development, and production [23]. Sun position, canopy shape, and leaf distribution all work together to carefully control the actual water loss under a north-south (N-S) canopy orientation. According to certain studies, canopy water loss along the N-S row direction was linearly related to estimated intercepted light, suggesting that crop architecture and light intensity both influence water usage. Water Use Efficiency varied owing to crop performance under various planting patterns. It was higher in the N-S orientation as compared to the east-west (E-W) directional sowing [24]. Leaf growth and development following planting is critical to crop growth and output. Pearl millet grain yield was found to be higher in the N-S direction than in the E-W direction, and yield was found to be connected with highest LAI and light interception in the N-S direction [25].

- **Nitrogen × water interaction:** Nitrogen (N) is one of the most significant fertilisers for crop productivity. The sensitivity of wheat crops to deficit watering and the combined use of N and phosphorus fertilizer remains unknown. Several research have been conducted to determine the best N application rates and timings for increased crop yield and grain quality [26]; [27]. Because of the greater mobility of N in soil, this nutrient is critical in soil fertility management [28]. Mineral fertiliser application is critical to resolving this issue. [29]. In some circumstances, the application of mineral fertilisers may have little influence on production when water is scarce [30]. Now-a-days the alternative approaches like Decision Support System (DSS) can take more practical implication under different environment. The Crop Simulation Model (CSM) studies can provide the optimum crop N and water requirements under varied soil- and climatic conditions. The losses of both N and water can happen in many ways if the management is not done properly. So, there is a for developing technologies that enhance Nitrogen Use Efficiency (NUE) and productive use of applied irrigation water leading to increased productivity. Crop Simulation Models (CSM) are capable of simulating the intricate relationships between weather, soil, and integrated management elements (water and N) that affect crop growth and development. As a result, these models can assist in synthesising much of the information gathered from the numerous experimental locations and providing this trustworthy knowledge to other places of interest with distinct soil-climatic features [31]. [32] reported that different levels of water and nitrogen application had an impact on the growth and development of the wheat crop, which was simulated using CERES (Crop Environment Resource Synthesis). The flood irrigation system wastes both irrigation water and applied nitrogen. Similarly, bed planting maize and wheat crops not only saves water but also increases NUE and grain output. [33] shown that wheat planting on beds yielded 15.1% more grain than flat planting at the same N rate. Using drip irrigation has been shown to save water and boost wheat production and water productivity. [34]; [35]. Drip fertigation enhanced the usage efficiency of applied nutrients in maize compared to flood irrigation [36].

The presence of enough plant nutrients and water in the root zone promotes leaf area expansion and growth [37], which improves light and CO₂ capture. According to several experimental research, wheat with the ideal levels of N treatment produce relatively higher LAI and intercept more radiation, resulting in

more biomass and grain yield [38]. It has been claimed that irrigation water applied at water-sensitive times (stem elongation, booting, anthesis, and early grain filling) in conjunction with appropriate fertilisation could result in increased production [39]; [40]. Higher intake fertilizers, on the other hand, results in reduced yield under rainfed (water starved) conditions. This might be due to the rainy season's rapid canopy development, followed by the extended dry spells that follow the end of the rainy season's rapid senescence, decreased translocation, grain production, and grain filling.[41]. Increasing water availability at low fertilizer levels, has been proven to result in low LAI and yield [42]. Recent research revealed that due to inadequate LAI, low canopy cover, reduced radiation interception, and increased evaporation, wheat plants receiving little to no nitrogen fertiliser treatment were unable to utilise irrigation water efficiently.[38].When enough water and nitrogen were available, the yield per unit water applied rose. This suggests that fertiliser (nutrient) supply has an effect on water productivity [43]; [44]; [38];[45]. Understanding the appropriate interplay of fertilizers and water may thus be critical for higher IWP and yield. [46] found that a high N fertiliser rate combined with moderate watering boosts IWP. IWP could be improved by reducing irrigation and increasing N supply. [45] underlined that prudent management measures in this sector are essential for better output and water productivity.

- **Irrigation techniques:** The major sector of using fresh water is agriculture and utilizes almost 70%, i.e., out of 2500 billion m³ 1500 billion m³ being utilized every year [47]; [48]; [49];[50]. In most developing countries, this fresh water is used in agriculture and loses up to 40% through evaporation, spills, and deep layer soil adsorption beyond the reach of roots. Today, it is commonly acknowledged that managing agricultural water is a significant challenge that is frequently correlated with problems related to development. Researchers have paid a lot of attention to water use efficiency as water scarcity continues to vary globally through time and geography as a result of climate change [51]. For the distribution of fresh water in agricultural fields, irrigation is only one method that has been practiced for more than 6000 years [52], but in the past 100 years, with the use of more advanced technology, it has become competent at meeting all demands for water productivity. The technique of irrigation scheduling involves a thorough understanding of the pattern of plant water use, which is influenced by factors such as weather, growth stage, and canopy moisture. It gives an idea of when to irrigate, how much water to apply, and what method should be used for improving irrigation use efficiency. Irrigation scheduling significantly affects water productivity since it controls the crop's water use and affects its yield [53]. The most commonly used irrigation scheduling is based on assessing soil-water harmony, which requires estimating crop evapotranspiration (ET_C). ET_C is generally determined by integrating potential (or) evapotranspiration (ET₀) measurements from meteorological data with crop coefficients. Previously, irrigation methods used gravity to apply and distribute water, however, improved methods such as drip irrigation, sprinkler irrigation, and smart irrigation methods are being used to minimize water losses [54];[55]. With the use of precision agriculture, in particular smart irrigation, farmers may conserve valuable resources without endangering plant health [56]. The description above makes it evident that in order to increase irrigation water use efficiency (WUE), losses throughout conveyance and distribution systems must be reduced, and the timing and quantity of water applied (or

irrigation schedule) must be optimized. When water is the primary constraint on productivity, improving the irrigation WUE may result in water savings that may be used to irrigate more areas.

- **Sprinkler irrigation:** The sprinkler irrigation strategy, a thorough irrigation technique, supports the scientific irrigation schedule. It's having some special equipment to use to carry pressurized water through uniform spraying to irrigate the land. Water use efficiency of crop can be improved with great potential by the sprinkler irrigation system because modern technologies use pipe to transport the water which limits conveyance water loss [57]. [58] provided a model to assess the effects of uniformity on agricultural production, which links yield response to evapotranspiration deficiencies at several growth stages. It is generally accepted that creating sprinkler irrigation uniformity is a crucial strategy for increasing crop output in sprinkler-irrigated areas while simultaneously saving water. Sprinkler irrigation systems with poor consistency, according to [59] lead to lower yields owing to water stress and waterlogging, which raises the cost of irrigation and causes other associated problems. Sprinkler irrigation uniformity also makes a significant contribution when taking into account the several elements influencing crop productivity in addition to evapotranspiration deficiencies [60]; [61]. Designing irrigation systems must take into account its impact on agricultural productivity. An irrigation system should apply water consistently so that every section of the irrigated area receives the same amount of water. Sadly, it appears that there is no way to make this happen [59]. Therefore, drip irrigation is more efficient to reduce crop water usage.
 - **Drip irrigation:** Subsurface drip irrigation was developed around 1959 in the USA, particularly in California [62] and Hawaii [63]. This drip irrigation, sometimes referred to as trickling irrigation, appears to be a potential solution to assist in resolving the water crisis. Additionally, it has the capacity to raise crop yields even with a lower irrigation water application [64] and to increase yields and water application efficiency to the point where water productivity is doubled or tripled [65]. Using plastic tubing positioned close to the root zone of the plants, drip irrigation is the steady, even distribution of low-pressure water to soil and plants. It serves as an alternative to the sprinkler and furrow irrigation techniques. Crops with high or low water requirements can employ drip irrigation. According to [66], Drip irrigation is a response to the increasing demand for limited freshwater resources, and it plays a significant part in the growth of WUE. Crops including grapes, cotton, tomato, sugarcane and bananas can all achieve output gains of 20–50% and water use reductions of 30–60% with drip irrigation [67]. Drip irrigation provides up to 95% irrigation efficiency, consumes 30–50% less water than surface irrigation, and minimizes salinization and water logging.
- 6. Precision agriculture technologies:** In order to maximise production while taking into consideration the dynamics of sustainable agricultural systems, precision agriculture is defined as the "application of technologies that integrate sensors, information systems, improved machinery, and informed management." [68]. With the use of precision agriculture, in particular smart irrigation, farmers may conserve valuable resources without endangering plant health [59]. Applying water to a field at the proper time,

volume, and location is referred to as smart irrigation [69]. Because of this, it necessitates the employment of monitoring and control systems for the best irrigation schedule while taking into account the variability in soil moisture conditions, shifting weather patterns, and plant physiological requirements. Natural resource management has found significant promise in the development and integration of several new technologies, including GIS (geographic information system), GPS (global positioning system), RS (remote sensing), Telecommunication, etc. [70]. The introduction of GPS technology enables precision agriculture that focuses mainly on positioning information in a practical and efficient manner for a few thousand dollar. And modernization of agriculture system with an expensive, high-precision differential GPS (DGPS) systems came out with the advanced features of centimetre accuracies [71] that allows for automated machinery guidance [72] and kinematic mapping of topography [73], and are more relevant in the creation of digital elevation models needed for terrain analysis [74]. This Precision agricultural technology focuses on water use efficiency [75]. Due to increasing water scarcity problems and adverse effects of climate change, water use efficiency with Precision agriculture grabbing the attention of many researchers [51]. For controlling the amount of water based on plant needs, real-time irrigation scheduling is very much important, thus several irrigation scheduling systems have been created to supply water accurately [76]. Smart irrigation is the water application in the field at the appropriate time, volume, and location [69]. Understanding the dynamics of moisture and its relation with the amount of irrigation water supplied to the crop field, the volume of water intake by the plant, and soil moisture available in the root zone area is crucial. It has been demonstrated that managing irrigation with a wireless sensor network (WSN) has resulted in water savings. WSN is a network of linked sensor nodes that interact with the environment directly and provide real-time data that is beneficial in identifying farm areas that need care, as its name indicates. It may be used for real-time monitoring as a tool for making decisions as well as collecting data.[77]. In addition to this prime role, an irrigation controller also plays a very important role in savings labour requirements and increasing efficiency in the use of water, energy, and fertilizer [78]. The following are the three main approaches to precise water management: (i) variable rate irrigation, (ii) drainage, and (iii) matching agronomic inputs to water availability determined by soil and/or landscape characteristics [78]. [79] defines a well-managed irrigation system is one that optimises the spatial and temporal allocation of water resources in order to encourage greater plant development and output and to increase agricultural production's economic efficiency (maximum net return).

- **Conservation agriculture (CA):** Worldwide, there is a hard movement for conservation agriculture, which is the practice of conducting agriculture in a way that does the least amount of environmental harm. The conservation tillage principle calls for zero tillage and low mechanical soil disturbance, which are both necessary to maintain the topsoil cover through crop residue retention. The observed proportionate growth in the number of moderate to micropores brought on by zero-tillage has an impact on the soil's ability to store water. According to [80], who discovered that water content at pF 2 changed more in combination with soil porosity than with organic matter content, water-holding capacity is connected to organic matter content, especially on sandy soils. Because of this, the water content at pF 2 was found to be higher in the top 6 cm of the zero-tilled soil than in the ploughed soil, but the opposite was true in the layer at 11-16 cm. According to [81], tilled plots retain less water than

untilled plots. According to [82], reduced tillage increased the soil pore space activity by improving the storage pores (0.5–50 mm) and the quantity of extended conduction pores (50–500 mm). They connected the increased microporosity in soils with minimal tillage to a rise in soil water content and, as a result, a rise in the amount of water that is accessible to plants. It has been discovered that topsoil (0–10 cm) that has been tilled has more water-holding capacity or moisture content than soil that has been ploughed.[83]. Additionally, non-tillage [84] and decreased tillage [83] systems have been shown to have higher water usage efficiency than Conservation tillage in soils. Therefore, the majority of research have proposed substituting conservation tillage for conventional tillage in order to improve soil water storage and water use efficiency (WUE) [85]; [86].

- **Antitranspirants:** Antitranspirants are substances that, when applied to plant leaves, can lower the rate of transpiration. Antitranspirants are often foliar sprays as water loss typically happens through the stomatal pores in the leaves, while they can occasionally be employed more conveniently as dips for submerging the above-ground plant portions, improving plant water potential [87]. Although ATs improved plant water status by reducing transpiration, their byproducts also delayed the absorption of carbon dioxide (CO₂) and, as a result, photosynthesis.[88]. Research is ongoing into ATs' ability to "waterproof" the most essential crop growth phases [89] by decreased transpiration and increased water use efficiency (WUE) under dry conditions. There are four types of antitranspirants:
 - **Reflective antitranspirants:** Reflective ATs are based on the principle of reflection to lower leaf temperature, which in consequence reduces the transpiration rate [90]. One of most reflective AT is kaolin, an aluminosilicate[91] particle film kaolin, which has improved reflecting qualities, reduces the heat loading on the surface of the leaf more than unfiltered kaolin because more infrared light and UV light are reflected [92]. Drought stress is necessary to lessen the detrimental impact of rising temperatures on crop physiology.. The fact that kaolin is regularly used to protect the fruit from the sun may mean that this isn't always the case.
 - **Metabolic or stomata-closing antitranspirants:** A class of chemicals known as metabolic ATs work on guard cells to cause partial stomatal closure by having hormone or hormone-like actions [93]. Exogenous abscisic acid (ABA) is widely used in this class, either alone or in conjunction with the synthetic (R)-cis-ABA, which is available commercially.[94]. Guard cells become flaccid and the stomata closes concurrently as a result of ABA signalling, which also causes the guard cells to release ions and water through osmosis. [95] (Kim et al., 2015). Fulvic acid is the other biostimulant-antitranspirant of the metabolic AT class. Organic matter breakdown produces fulvic acid, which dissolves in both alkaline and acidic liquids [95]; [96]. [97]found that Fulvic acid was sprayed to maize at the tasselling stage, and while transpiration rate, net photosynthesis, and WUE were all greatly enhanced, stomatal conductance improved only marginally (13%). This suggests that fulvic acid functioned as a biostimulant. Metabolic AT research frequently focused on phenyl mercuric acetate (PMA), which was later discovered to be hazardous [98]. According to [99] and [100], India appears to be the only nation where using PMA as an AT is still permitted.

- Film-forming antitranspirants:** The majority of the currently accessible film-forming ATs are organic polymers that can be emulsified in water and form films after a spraying treatment has dried [100]. To minimise transpiration water loss, the films function as a physical barrier across the stomata. The oldest film-forming AT is di-1-p-menthene (pinolene), with Williamson being one of the early mentions (1963). [102] examined the drought-relieving effects of di-1-p-menthene and poly-1-p-menthene on oil seed rape in glasshouse settings. Both substances markedly decreased gas exchange, but di-1-p-menthene was superior at suppressing stomatal conductance (by 50% vs 11%) and did so for a longer duration (> 14 days against 9 days). The results of the yield component were consistent with the stomatal conductance measurements, and di-1-p-menthene had higher values for seed biomass and the number of pods per plant, showing that the increased WUE more than made up for the decreased CO₂ fixation.
- Soil Conditioners:** In order to produce food, agriculture depends heavily on water. But water shortages and droughts have caused soil salinization and desiccation, endangering both the viability of agriculture and the supply of food. Therefore, increasing water consumption efficiency is crucial for agriculture [103]. Superabsorbent polymers (SAPs) can be used to improve water use in agriculture by keeping moisture in the soil and using less irrigation water because of their extremely high-water absorption and retention capacities [104]. The chain of SAPs contains a large number of hydrophilic groups that aid in absorbing water hundreds to thousands of times their own mass. Additionally, three-dimensional networks that are connected chemically or physically ensure SAPs have a significant capacity to retain water even under pressure [105]. While SAPs made of synthetic polymers, such as polyacrylic acid (PAA) and polyacrylamide (PAM), offer benefits like low cost, longer service life, and high water-absorption rate, their non-degradation qualities might have a negative influence on the environment and plant development.

III. CONCLUSION

Seed priming, maintaining proper row-direction of crops, adhering to wise nutrient management practices to leverage the positive water-nutrient interaction, minimising water application via drip and sprinkler irrigation or optimising the same via precision irrigation approaches, reducing unproductive water losses through conservation agricultural practices, or applying antitranspirants can all increase water productivity or crop water use efficiency on a field scale. Finding the best effective combination of choices to increase water productivity is difficult and heavily influenced by the farmers' financial resources.

REFERENCES

- [1] Viets, F. G. (1962), "Fertilizers and the efficient use of water". *Advances in agronomy*, 14, 223-264.
- [2] Israelsen, O. W. (1932), "Irrigation principles and practices". *Irrigation principles and practices*.
- [3] Sharma, B., Amarasinghe, U., Xueliang, C., de Condappa, D., Shah, T., Mukherji, A., and Smakhtin, V. (2013), "The Indus and the Ganges: river basins under extreme pressure," In *Water, Food and Poverty in River Basins* (pp. 40-68). Routledge.

- [4] Molden, D. (2013), “*Water for food water for life: A comprehensive assessment of water management in agriculture*,” Routledge.
- [5] Cook, P. G. (2013), “Estimating groundwater discharge to rivers from river chemistry surveys,” *Hydrological Processes*, 27(25), 3694-3707.
- [6] Molden, D., Murray-Rust, H., Sakthivadivel, R., and Makin, I. (2003), “A water-productivity framework for understanding and action,” *Water productivity in agriculture: Limits and opportunities for improvement*, 1.
- [7] Scanlon, B. R., Healy, R. W., and Cook, P. G. (2002), “Choosing appropriate techniques for quantifying groundwater recharge,” *Hydrogeology journal*, 10(1), 18-39.
- [8] Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F. T. (2010), “Groundwater use for irrigation—a global inventory,” *Hydrology and earth system sciences*, 14(10), 1863-1880.
- [9] Assouline, S., Russo, D., Silber, A., and Or, D. (2015), “Balancing water scarcity and quality for sustainable irrigated agriculture,” *Water Resources Research*, 51(5), 3419-3436.
- [10] Amarasingha, R. P. R. K., Suriyagoda, L. D. B., Marambe, B., Rathnayake, W. M. U. K., Gaydon, D. S., Galagedara, L. W., and Howden, M. (2017), “Improving water productivity in moisture-limited rice-based cropping systems through incorporation of maize and mungbean: A modelling approach,” *Agricultural water management*, 189, 111-122.
- [11] Ashraf Vaghefi, S., Abbaspour, K. C., Faramarzi, M., Srinivasan, R., and Arnold, J. G. (2017), “Modeling crop water productivity using a coupled SWAT–MODSIM model,” *Water*, 9(3), 157.
- [12] Evans, R. G., and Sadler, E. J. (2008), “Methods and technologies to improve efficiency of water use,” *Water resources research*, 44(7).
- [13] Karandish, F., and Šimůnek, J. (2016), “A field-modeling study for assessing temporal variations of soil-water-crop interactions under water-saving irrigation strategies,” *Agricultural water management*, 178, 291-303.
- [14] Austin, R., Longden, P. C., and Hutchinson, J. (1969). “Some effects of ‘hardening’ carrot seed,” *Annals of Botany*, 33(5), 883-895.
- [15] Longden, P. C. (1971), “Advanced sugar-beet seed,” *The Journal of Agricultural Science*, 77(1), 43-46.
- [16] McDonald, M. B. (2000). Seed priming. *Seed technology and its biological basis*. Sheffield Academic Press, Sheffield, 287-325.
- [17] Pill, W. G., Frett, J. J., & Morneau, D. C. (1991). Germination and seedling emergence of primed tomato and asparagus seeds under adverse conditions. *HortScience*, 26(9), 1160-1162.
- [18] Paparella, S., Araújo, S. S., Rossi, G., Wijayasinghe, M., Carbonera, D., & Balestrazzi, A. (2015). Seed priming: state of the art and new perspectives. *Plant cell reports*, 34(8), 1281-1293.
- [19] Taylor, A. G., Allen, P. S., Bennett, M. A., Bradford, K. J., Burris, J. S., & Misra, M. K. (1998). Seed enhancements. *Seed science research*, 8(2), 245-256.
- [20] Passam, H. C., Karavites, P. I., Papandreou, A. A., Thanos, C. A., & Georghiou, K. (1989). Osmoconditioning of seeds in relation to growth and fruit yield of aubergine, pepper, cucumber and melon in unheated greenhouse cultivation. *Scientia Horticulturae*, 38(3-4), 207-216.
- [21] Muhyaddin, T., & Wiebe, H. J. (1987). Influence of PEG [polyethylene glycol] seed treatments on emergence under stress conditions. *Acta Horticulturae (Netherlands)*.
- [22] Rajjou, L., Duval, M., Gallardo, K., Catusse, J., Bally, J., Job, C., & Job, D. (2012). Seed germination and vigor. *Annual review of plant biology*, 63(507), 2012.
- [23] Micheletto, S., Rodriguez-Urbe, L., Hernandez, R., Richins, R. D., Curry, J., & O’Connell, M. A. (2007). Comparative transcript profiling in roots of *Phaseolus acutifolius* and *P. vulgaris* under water deficit stress. *Plant Science*, 173(5), 510-520.
- [24] Dhaliwal, L. K., Buttar, G. S., Kingra, P. K., Singh, S., & Kaur, S. (2019). Effect of mulching, row direction and spacing on microclimate and wheat yield at Ludhiana. *Journal of Agrometeorology*, 21(1), 42-45.

- [25] Faiz, M. A., Dhar, S., Baray, S. M., Dass, A., & Khalili, A. (2018). Effect of row spacing and sowing direction on growth attributes of wheat varieties in Kandahar region of Afghanistan. *New Series Vol. 39*, 229.
- [26] Pattey, E., Strachan, I. B., Boisvert, J. B., Desjardins, R. L., & McLaughlin, N. B. (2001). Detecting effects of nitrogen rate and weather on corn growth using micrometeorological and hyperspectral reflectance measurements. *Agricultural and forest meteorology*, 108(2), 85-99.
- [27] Weisz, R., Crozier, C. R., & Heiniger, R. W. (2001). Optimizing nitrogen application timing in no-till soft red winter wheat. *Agronomy Journal*, 93(2), 435-442.
- [28] MoARD, 2006. Crop Variety Register. Issue No. 9. Crop Development Department. Addis Abbaba, Ethiopia.
- [29] Habtegebrial, K., & Singh, B. R. (2006). Effects of timing of nitrogen and sulphur fertilizers on yield, nitrogen, and sulphur contents of Tef (*Eragrostis tef* (Zucc.) Trotter). *Nutrient Cycling in Agroecosystems*, 75(1), 213-222.
- [30] El Mejahed, K., & Aouragh, L. (2005). Green-manure and nitrogen-fertilizer effects on soil quality and profitability of a wheat-based system in semiarid Morocco. *Management of Nutrients and Water in Rainfed Arid and Semi-arid Areas for Increasing Crop Production, IAEA Tecdoc.(this volume)*, 89-106.
- [31] Rusan, M. J. M., Battikhi, A., & Zuraiqi, S. (2005). Enhancement of nitrogen-and water-use efficiency by optimizing the combined management of soil, crop and nitrogen. *Management of Nutrients and Water in Rainfed Arid and Semi-arid Areas for Increasing Crop Production, IAEA Tecdoc.(this volume)*, 155-178.
- [32] Ritchie, J. T., Singh, U., Godwin, D. C., & Bowen, W. T. (1998). Cereal growth, development and yield. In *Understanding options for agricultural production* (pp. 79-98). Springer, Dordrecht.
- [33] Majeed, A., Muhmood, A., Niaz, A., Javid, S., Ahmad, Z. A., Shah, S. S. H., & Shah, A. H. (2015). Bed planting of wheat (*Triticum aestivum* L.) improves nitrogen use efficiency and grain yield compared to flat planting. *The crop journal*, 3(2), 118-124.
- [34] Wang, J., Gong, S., Xu, D., Yu, Y., & Zhao, Y. (2013). Impact of drip and level-basin irrigation on growth and yield of winter wheat in the North China Plain. *Irrigation science*, 31(5), 1025-1037.
- [35] Chen, R., Cheng, W., Cui, J., Liao, J., Fan, H., Zheng, Z., & Ma, F. (2015). Lateral spacing in drip-irrigated wheat: The effects on soil moisture, yield, and water use efficiency. *Field Crops Research*, 179, 52-62.
- [36] Sampathkumar, T., & Pandian, B. J. (2010). Efficiency of applied nutrients and SPAD values in hybrid maize under drip fertigation. *Madras Agric. J*, 97(7-9), 237-241.
- [37] Kibe, A. M., Singh, S., & Kalra, N. (2006). Water–nitrogen relationships for wheat growth and productivity in late sown conditions. *Agricultural Water Management*, 84(3), 221-228.
- [38] Caviglia, O. P., & Sadras, V. O. (2001). Effect of nitrogen supply on crop conductance, water- and radiation-use efficiency of wheat. *Field Crops Research*, 69(3), 259-266.
- [39] Zhang, H., & Oweis, T. (1999). Water–yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. *Agricultural water management*, 38(3), 195-211.
- [40] Huang, M., Gallichand, J., & Zhong, L. (2004). Water–yield relationships and optimal water management for winter wheat in the Loess Plateau of China. *Irrigation Science*, 23(2), 47-54.
- [41] Giunta, F., Motzo, R., & Deidda, M. (1993). Effect of drought on yield and yield components of durum wheat and triticale in a Mediterranean environment. *Field Crops Res.*, 33(4): 399-409.
- [42] Montazar, A., & Mohseni, M. (2011). Optimizing wheat water productivity as affected by irrigation and fertilizer-nitrogen regimes in an arid environment. *Journal of Agricultural Science*, 3(3), 143.
- [43] Zhang, H., Oweis, T. Y., Garabet, S., & Pala, M. (1998). Water-use efficiency and transpiration efficiency of wheat under rain-fed conditions and supplemental irrigation in a Mediterranean-type environment. *Plant and Soil*, 201(2), 295-305.
- [44] Oweis, T., Zhang, H., & Pala, M. (2000). Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. *Agronomy journal*, 92(2), 231-238.

- [45] Mandal, K. G., Hati, K. M., Misra, A. K., Bandyopadhyay, K. K., & Mohanty, M. (2005). Irrigation and nutrient effects on growth and water–yield relationship of wheat (*Triticum aestivum* L.) in central India. *Journal of Agronomy and Crop Science*, 191(6), 416–425.
- [46] Wang, Q., Li, F., Zhang, E., Li, G., & Vance, M. (2012). The effects of irrigation and nitrogen application rates on yield of spring wheat (longfu-920), and water use efficiency and nitrate nitrogen accumulation in soil. *Australian journal of crop science*, 6(4), 662–672.
- [47] Giagnocavo, C., Bienvenido, F., Ming, L., Yurong, Z., Sanchez-Molina, J.A., Xinting, Y., 2017. Agricultural cooperatives and the role of organisational models in new intelligent traceability systems and big data analysis. *Int. J. Agric. Biol. Eng.* 10, 115–125.
- [48] Luo, X., Liao, J., Zang, Y., Zhou, Z., 2016. Improving agricultural mechanization level to promote agricultural sustainable development. *Trans. Chinese Soc. Agric. Eng.* 32, 1–11.
- [49] Shah, N.G., 2012. Precision irrigation: sensor network based irrigation. *IntechOpen*.
- [50] Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.-J., 2017. Big data in smart farming—a review. *Agric. Syst.* 153, 69–80.
- [51] Hess, T.M., Knox, J.W., 2013. Water savings in irrigated agriculture: A framework for assessing technology and management options to reduce water losses. *Outlook Agric.* 42, 85–91.
- [52] Postel, S., 1999. Pillar of sand: can the irrigation miracle last? WW Norton & Company.
- [53] Pardossi, A., Incrocci, L., Incrocci, G., Malorgio, F., Battista, P., Bacci, L., Rapi, B., Marzalletti, P., Hemming, J., Balendonck, J., 2009. Root zone sensors for irrigation management in intensive agriculture. *Sensors* 9, 2809–2835.
- [54] Liu, X., Feike, T., Chen, S., Shao, L., Sun, H., Zhang, X., 2016. Effects of saline irrigation on soil salt accumulation and grain yield in the winter wheat-summer maize double cropping system in the low plain of North China. *J. Integr. Agric.* 15, 2886–2898.
- [55] Ming, Z., Xinqun, Z., Zhifen, Z., 2016. Research progresses in technological innovation and integration of agricultural engineering. *Int. J. Agric. Biol. Eng.* 9, 1–9.
- [56] Pierce, F.J., 2010. Precision irrigation. *Landbauforsch SH 340*, 45–56.
- [57] Kahlowan, M.A., Raouf, A., Zubair, M., Kemper, W.D., 2007. Water use efficiency and economic feasibility of growing rice and wheat with sprinkler irrigation in the Indus Basin of Pakistan. *Agric. water Manag.* 87, 292–298.
- [58] Li, J., 1998. Modeling crop yield as affected by uniformity of sprinkler irrigation system. *Agric. Water Manag.* 38, 135–146.
- [59] Darko, R.O., Shouqi, Y., Junping, L., Haofang, Y., Xingye, Z., 2017. Overview of advances in improving uniformity and water use efficiency of sprinkler irrigation. *Int. J. Agric. Biol. Eng.* 10, 1–15.
- [60] Dechmi, F., Playán, E., Cavero, J., Faci, J.M., Martínez-Cob, A., 2003. Wind effects on solid set sprinkler irrigation depth and yield of maize (*Zea mays*). *Irrig. Sci.* 22, 67–77.
- [61] Varlev, I., 1976. Evaluation of nonuniformity in irrigation and yield. *J. Irrig. Drain. Div.* 102, 149–164.
- [62] Davis, S., 1967. SUBSURFACE IRRIGATION, HOW SOON A REALITY. *Agric. Eng. VOL 48, NO 11, P 654-655, Novemb. 1967. 5 FIG.*
- [63] Vaziri, C.M., Gibson, W., 1972. Subsurface and drip irrigation for Hawaiian sugarcane. *Rep Hawaii Sugar Technol Annu Con.*
- [64] Yohannes, F., Tadesse, T., 1998. Effect of drip and furrow irrigation and plant spacing on yield of tomato at Dire Dawa, Ethiopia. *Agric. Water Manag.* 35, 201–207.
- [65] Postel, S.L., 2000. Entering an era of water scarcity: the challenges ahead. *Ecol. Appl.* 10, 941–948.
- [66] Quezada, C., Fischer, S., Campos, J., Ardiles, D., 2011. Water requirements and water use efficiency of carrot under drip irrigation in a haploxerand soil. *J. soil Sci. plant Nutr.* 11, 16–28.
- [67] Sivanappan, R.K., 1994. Prospects of micro-irrigation in India. *Irrig. Drain. Syst.* 8, 49–58.
- [68] Yin, H., Cao, Y., Marelli, B., Zeng, X., Mason, A.J., Cao, C., 2021. Soil sensors and plant wearables for smart and precision agriculture. *Adv. Mater.* 33, 2007764.

- [69] Singh, G., Sharma, D., Goap, A., Sehgal, S., Shukla, A.K., Kumar, S., 2019. Machine Learning based soil moisture prediction for Internet of Things based Smart Irrigation System, in: 2019 5th International Conference on Signal Processing, Computing and Control (ISPCC). IEEE, pp. 175–180.
- [70] Gibbons, G., 2000. Turning a farm art into science-an overview of precision farming. URL <http://www.precisionfarming.com>.
- [71] Lange, A.F., 1996. Centimeter accuracy differential GPS for precision agriculture applications, in: Proceedings of the Third International Conference on Precision Agriculture. Wiley Online Library, pp. 675–680.
- [72] O'Connor, M., Bell, T., Elkaim, G., Parkinson, B., 1996. Automatic steering of farm vehicles using GPS, in: Proceedings of the Third International Conference on Precision Agriculture. Wiley Online Library, pp. 767–777.
- [73] Clark, R.L., 1996. A comparison of rapid GPS techniques for topographic mapping, in: Proceedings of the Third International Conference on Precision Agriculture. Wiley Online Library, pp. 651–662.
- [74] Moore, I.D., Gessler, P.E., Nielsen, G.A.E., Peterson, G.A., 1993. Soil attribute prediction using terrain analysis. *Soil Sci. Soc. Am. J.* 57, 443–452.
- [75] Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. *Water Resour. Res.* 44.
- [76] Andales, A., 2019. Irrigation scheduling using a water balance model and soil moisture sensors, in: Proceedings of the 31st Annual Central Plains Irrigation Conference, Kearney, Nebraska, Feb. 26-27.
- [77] Nawandar, N.K., Satpute, V.R., 2019. IoT based low cost and intelligent module for smart irrigation system. *Comput. Electron. Agric.* 162, 979–990.
- [78] Boman, B., Smith, S., Tullios, B., 2006. Control and automation in citrus microirrigation systems. Doc. No. CH194. Inst. Food Agric. Sci. Univ. Florida Gainesville, Florida.
- [79] Hillel, D., 1990. Role of irrigation in agricultural systems. *Agronomy* 5–30.
- [80] van Ouwerkerk, C. van, Boone, F.R., 1970. Soil-physical aspects of zero-tillage experiments. *Netherlands J. Agric. Sci.* 18, 247–261.
- [81] Kargas, G., Kerkides, P., Poulouvassilis, A., 2012. Infiltration of rain water in semi-arid areas under three land surface treatments. *Soil Tillage Res.* 120, 15–24.
- [82] Pagliani, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. *Soil Tillage Res.* 79, 131–143.
- [83] McVay, K.A., Budde, J.A., Fabrizzi, K., Mikha, M.M., Rice, C.W., Schlegel, A.J., Peterson, D.E., Sweeney, D.W., Thompson, C., 2006. Management effects on soil physical properties in long-term tillage studies in Kansas. *Soil Sci. Soc. Am. J.* 70, 434–438.
- [84] Li, L.L., Huang, G.B., Zhang, R.Z., Jin, X.J., Li, G.D., Chan, K.Y., 2005. Effects of conservation tillage on soil water regimes in rainfed areas. *Acta Ecol. Sin.* 25, 2326–2332.
- [85] Fabrizzi, K.P., Garcia, F.O., Costa, J.L., Picone, L.I., 2005. Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. *Soil Tillage Res.* 81, 57–69.
- [86] Silburn, D.M., Freebairn, D.M., Rattray, D.J., 2007. Tillage and the environment in sub-tropical Australia—Tradeoffs and challenges. *Soil Tillage Res.* 97, 306–317.
- [87] Del Amor, F.M., Cuadra-Crespo, P., Walker, D.J., Cámara, J.M., Madrid, R., 2010. Effect of foliar application of antitranspirant on photosynthesis and water relations of pepper plants under different levels of CO₂ and water stress. *J. Plant Physiol.* 167, 1232–1238.
- [88] Kettlewell, P.S., Heath, W.L., Haigh, I.M., 2010. Yield enhancement of droughted wheat by film antitranspirant application: rationale and evidence. *Agric. Sci.* 1, 143.
- [89] Kettlewell, P.S., 2014. Waterproofing wheat—a re-evaluation of film antitranspirants in the context of reproductive drought physiology. *Outlook Agric.* 43, 25–29.
- [90] Glenn, D.M., 2012. The mechanisms of plant stress mitigation by kaolin-based particle films and applications in horticultural and agricultural crops. *HortScience* 47, 710–711.
- [91] Cantore, V., Pace, B., Albrizio, R., 2009. Kaolin-based particle film technology affects tomato

- physiology, yield and quality. *Environ. Exp. Bot.* 66, 279–288.
- [92] Brito, C., Dinis, L.-T., Moutinho-Pereira, J., Correia, C., 2019. Kaolin, an emerging tool to alleviate the effects of abiotic stresses on crop performance. *Sci. Hortic. (Amsterdam)*. 250, 310–316.
- [93] AbdAllah, A.M., Burkey, K.O., Mashheet, A.M., 2018. Reduction of plant water consumption through anti-transpirants foliar application in tomato plants (*Solanum lycopersicum* L.). *Sci. Hortic. (Amsterdam)*. 235, 373–381.
- [94] Li, J., Li, C., Smith, S.M., 2017. Hormone metabolism and signaling in plants. Academic press.
- [95] Kim, J., Malladi, A., Van Iersel, M.W., 2015. Erratum: Physiological and molecular responses to drought in *Petunia*: The importance of stress severity (*Journal of Experimental Botany* (2012) 63: 18 (6335-6345). *J. Exp. Bot.* 66, 419.
- [96] Klucakova, M., Pelikan, P., Lapcik, L., Lapcikova, B., Kucerik, J., Kalab, M., 2000. Structure and properties of humic and fulvic acids. I. Properties and reactivity of humic acids and fulvic acids. *J. Polym. Mater.* 17, 337–356.
- [97] Anjum, S.A., Wang, L., Farooq, M., Xue, L., Ali, S., 2011. Fulvic acid application improves the agricultural Systems. Wiley Online Library, pp. 209–227.
- [98] Das, V.S.R., Raghavendra, A.S., 1979. Antitranspirants for improvement of water use efficiency of crops. *Outlook Agric.* 10, 92–98.
- [99] Pandey, P.P., Sharma, R., Neelkanthe, S.S., 2017. Climate change: Combating drought with antitranspirants and super absorbent. *Plant Arch.* 17, 1146–1156.
- [100] Kumar, K., Kumar, Y., Katiyar, N.K., 2018. Effect of plant geometry, nitrogen level and antitranspirants on physiological growth, yield attributes, WUE and economics of mustard (*Brassica juncea*) under semiarid conditions of western Uttar Pradesh. *J. Pharmacogn. Phytochem.* 7, 226–229.
- [101] Moftah, A., Al-Humaid, A., 2005. Effects of antitranspirants on water relations and photosynthetic rate of cultivated tropical plant (*Polianthes tuberosa* L.). *Polish J. Ecol.* 53, 165–175.
- [102] Faralli, M., Grove, I.G., Hare, M.C., Boyle, R.D., Williams, K.S., Corke, F.M.K., Kettlewell, P.S., 2016. Canopy application of film antitranspirants over the reproductive phase enhances yield and yield-related physiological traits of water-stressed oilseed rape (*Brassica napus*). *Crop Pasture Sci.* 67, 751–765.
- [103] Thombare, N., Mishra, S., Siddiqui, M.Z., Jha, U., Singh, D., Mahajan, G.R., 2018. Design and development of guar gum based novel, superabsorbent and moisture retaining hydrogels for agricultural applications. *Carbohydr. Polym.* 185, 169–178.
- [104] Guilherme, M.R., Aouada, F.A., Fajardo, A.R., Martins, A.F., Paulino, A.T., Davi, M.F.T., Rubira, A.F., Muniz, E.C., 2015. Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: A review. *Eur. Polym. J.* 72, 365–385.
- [105] Demitri, C., Scalera, F., Madaghiele, M., Sannino, A., Maffezzoli, A., 2013. Potential of cellulose-based superabsorbent hydrogels as water reservoir in agriculture. *Int. J. Polym. Sci.* 2013.