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Review

From managed aquifer recharge to soil aquifer treatment on agricultural soils: Concepts and challenges

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ABSTRACT

Water is a limiting factor for economic and social development in most arid and semi-arid regions on Earth. The deliberate recharge of depleted aquifer storage and later recovery, known as managed aquifer recharge (MAR), is an important tool for water management and sustainability. Increasing stresses on groundwater and subsequent overdrafts have sparked the development of several advanced MAR technologies, including soil aquifer treatment (SAT). SAT is a method that recharges wastewater effluent through intermittent percolation in infiltration basins. Another emerging MAR approach currently explored is the off-season flooding of agricultural lands, known as agricultural MAR, or Ag-MAR. Utilizing agricultural fields as temporary infiltration basins during periods of dormancy increases the availability of land resources for groundwater recharge, rather than designating land explicitly for MAR. As land resources for SAT become limited and the amount of available treated wastewater (TWW) increases, we propose the idea of agricultural SAT, or Ag-SAT, as a combination of SAT and Ag-MAR. This review paper aims to provide an in-depth look into the approach and application of Ag-MAR and the possibilities of integrating Ag-MAR with SAT. Ag-SAT comprises the off-season flooding of agricultural land using TWW for groundwater recharge and subsequent reuse. Ag-SAT could provide alternative infiltration sites for SAT where available surface area dedicated to infiltration is becoming a limiting factor. Additionally, the treated wastewater could potentially provide nutrients to agricultural fields during the flooding cycles. Potential advantages, disadvantages, and knowledge gaps related to Ag-SAT are presented and discussed.

1. Introduction

Groundwater extraction enables food security, drought relief, and economic growth. Nevertheless, the development of groundwater usage often causes water levels to decrease (Gleeson et al., 2010; Konikow and Kendy, 2005). The depletion of groundwater by human activities constitutes a major threat to drinking water supplies and irrigated agriculture. Over-exploitation of aquifers may result in irreversible damage and future deprivation of this crucial resource (Clark et al., 1996). Many regions worldwide depend primarily on groundwater as a water source for different uses (e.g., domestic, industrial, municipal, agricultural, and environmental). Over 30% of the world's population relies on groundwater for their drinking water supply and over 40% relies on it for agricultural irrigation (FAO, 2011). The continual stress on groundwater by the abstraction of water and the resulting lowered groundwater levels have caused severe environmental harm, including groundwater salinization (intrusion of salt water), particularly threatening coastal aquifers (Tomaszkiewicz et al., 2014; Wada et al., 2010). Additionally, anthropogenic activities have introduced a wide variety of contaminants and pollutants to groundwater, subsequently deteriorating its quality. Nitrate is considered one of the most common groundwater contaminants, particularly in agricultural regions, due to the use of nitrogen-rich fertilizers, limited denitrification, and improper disposal of human and animal waste in catchment basins. Other hazardous contaminants include emerging organic micropollutants (pharmaceuticals, personal care products, and other synthetic organic compounds), pesticides and herbicides, heavy metals, and pathogens (Kurwadkar and Venkataraman, 2013). Groundwater demand is higher than ever due to rapid population growth and the resulting increase in food demand, as well as industrial development and climate change (e.g., desertification). As a

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result, in many places, groundwater pumping exceeds natural recharge (Bierkens and Wada, 2019). In order to cope and prevent future depletion and deterioration, effective long-term management strategies must be implemented.

Groundwater storage balance comprises inputs and outputs. Inputs include natural recharge (e.g., precipitation, surface water), recharge from surface water-based irrigation, and managed aquifer recharge. Outputs include natural discharge (e.g., flow to streams, lakes and, in coastal aquifers, the ocean; evapotranspiration) and anthropogenic pumping (Scanlon et al., 2016). Methods to recharge groundwater aquifers are vital for increasing the depleted groundwater storage. These can be categorized into managed, unmanaged, and unintentional (e.g., deep seepage under irrigation) (Dillon et al., 2009). In general, the managed methods include infiltration basins and direct injection via wells (Casanova et al., 2016; Dillon, 2005). Unmanaged methods include drainage wells and leaching from septic tanks, usually for water disposal without recovery or reuse (Dillon et al., 2009). Managed aquifer recharge (MAR) comprises a variety of methods that intentionally divert, transport, store, infiltrate, and recharge excess surface water into aquifers during a wet period for subsequent recovery during dry periods or for environmental benefit (Bouwer, 2002; Dillon et al., 2009; Kocis and Dahlke, 2017; Scanlon et al., 2016). The principal objectives of MAR include: (1) storage of excess water during the wet period for later use in dry periods (mainly in arid/semi-arid regions); (2) the introduction of a water treatment barrier (improving water quality for future specific use); (3) the creation of a hydraulic barrier that prevents seawater intrusion (e.g., in coastal regions) (Aharoni et al., 2011; Parimalarenganayaki, 2020); and (4) flood control (Deiminiat et al., 2011; Standen et al., 2020). There are numerous and varied MAR technologies and configurations used to meet a variety of conditions and constraints, depending on the recovered water's purpose (e.g., drinking, irrigation, hygiene, sustaining ecosystems, or industrial water and recreation (Page et al., 2018)). MAR is a dynamic approach that can utilize different water sources in order to sustain the recharge system, depending on the infrastructure and system goals. These include stream water (Scanlon et al., 2016), stormwater (Page et al., 2016), desalinated seawater (Dillon et al., 2009), and treated wastewater (TWW) (Zuurbier et al., 2018). Common MAR methods are listed and described in Table 1.

Dillion et al. (2019) recently investigated the global progress of MAR in recent decades. Their survey shows that over the last 60 years, the world has slowly adopted MAR methods to replenish depleted aquifers and to improve groundwater quality with recharge water. Since the widespread introduction of MAR in the 1960s, groundwater recharge has accelerated at a rate of about 5% per year. Data collected from 15 countries (that account for 34% of global groundwater use in 2010) showed that in 1965, the total MAR capacity was around 1 km^3 per year. Data collected from 2015 showed that the MAR capacity has grown to about 10 km^3 per year. India and the USA are currently world leaders in MAR (in terms of volume) and have increased their MAR volumes from 154 and 302 Mm^3 in 1965–3070 and 2569 Mm^3 in 2015, respectively. Some other prominent countries practicing MAR include Australia, Italy, Israel, Germany, and Spain, reporting MAR volumes of 410, 461, 134, 870, and 380 Mm^3 in 2015, respectively. The rise in MAR applications is credited to amassed research, improved operating practices, reliability, and public acceptance and awareness of the dire lack and constant depletion of groundwater. Although there has been a substantial increase in MAR usage worldwide, to date, the authors estimate that intentional recharge makes up less than 3% of groundwater extraction in countries reported to use MAR or approximately 1% of global groundwater extraction, ultimately demonstrating that MAR is not keeping pace with the global rate of groundwater depletion.

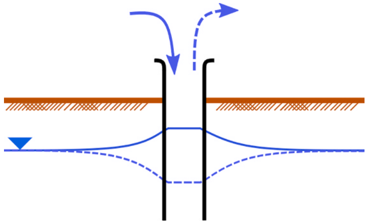
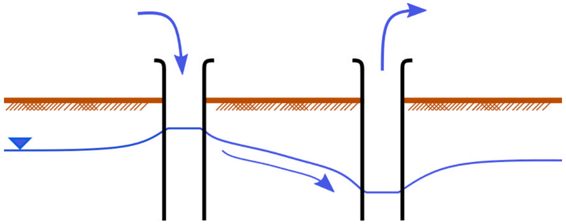
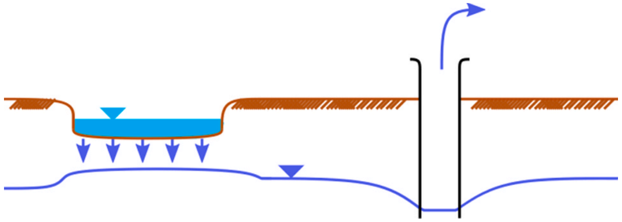
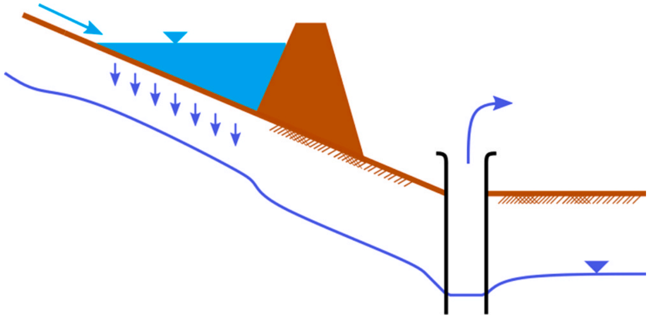
2. Agricultural managed aquifer recharge (Ag-MAR)

Acquiring land suitable for MAR is challenging (Crites et al., 2006; O'Geen et al., 2015), and land resources are a limiting factor in many MAR projects' implementation. Thus, an emerging approach to enhance aquifer recharge is the development of MAR projects on agricultural lands, known as agricultural managed aquifer recharge (Ag-MAR). To date, Ag-MAR has not been thoroughly investigated. However, it is believed that this approach holds potential benefits over conventional MAR methods (Harter and Dahlke, 2014; Kocis and Dahlke, 2017). Ag-MAR can be executed on vast agricultural landscapes during periods when no crops are being grown or while many crop species are in a dormant period. Examples include deciduous orchards, such as almonds, pomegranates, and pistachios, during the winter chill. A photo demonstrating Ag-MAR can be seen in Fig. 1. Orchards with evergreen trees, such as citrus, can also be used as long as they are grafted onto tolerant rootstocks and/or planted on a raised soil bed (i.e. ridge). Thus, one of Ag-MAR's advantages is that agricultural plots can serve as temporary infiltration sites, instead of allocating land specifically for MAR. By doing so, Ag-MAR avoids competition over land, which is an important issue, especially in urban areas (Niswonger et al., 2017). Although Ag-MAR is a promising approach, several parameters affect its feasibility, primarily concerning the crop's health and yield when introduced to ponding conditions. The crop's well-being is influenced by its ability to withstand flooded conditions in the root zone. Under waterlogged conditions, decreased root health may result in lower nutrient uptake, diminishing crop yields (Dahlke et al., 2018b). Another risk that needs to be considered is groundwater contamination following enhanced artificial recharge. This occurs due to higher water fluxes that percolate through the vadose zone, accompanied by agricultural fertilizers, pesticides, and herbicides (Nielsen and Lee, 1987) that might leach during water application. Additional factors include water availability for recharge, appropriate infrastructure, soil physical and biochemical properties, effect on groundwater quality, water law regulations, and fiscal expenses (Dahlke et al., 2018b).

Determining the suitability of a given agricultural site for Ag-MAR purposes is a complex process. Its success depends on many parameters. O'Geen et al. (2015) developed a soil suitability index that identifies potential locations for groundwater banking (large-scale storage of water in aquifers for later use) on agricultural lands. It is known as the Soil Agricultural Groundwater Banking Index (SAGBI) and is based on the emerging strategy of applying water to agricultural lands outside the typical irrigation season for the purpose of groundwater recharge. SAGBI considers five soil factors: (1) *deep percolation*: highly permeable soils that enable water passage beyond the root zone (approximately 1.5 m); (2) *root zone residence time*: the duration of waterlogged root zone conditions after water application must be acceptable for the crops; (3) *topography*: leveled fields with low-percentage slopes are better suited for holding water in the landscape, permitting infiltration across large areas, while reducing ponding and minimizing erosion by runoff; (4) *chemical limitations*: high soil salinity might result in saline leachate that negatively affects groundwater quality; and (5) *soil surface condition*: application of large volumes of "standing" water may lead to soil erosion (e.g., aggregate destruction, compaction and formation of crusts), which may severely limit infiltration. It is important to note that the deep percolation and root zone residence time factors are typically more important than the other factors due to their greater relevance in groundwater recharge. Other factors can be altered for improved results, thus carrying a lower weight. Based on these factors, agricultural soils are scored on their overall Ag-MAR potential capabilities (O'Geen et al., 2015). Fig. 2 summarizes the major benefits and drawbacks of implementing Ag-MAR.

The approach of off-season Ag-MAR is relatively new. As such, its regional-scale water resources and environmental benefits and drawbacks have not yet been explored in depth (Kourakos et al., 2019). Niswonger et al. (2017) developed a complex and comprehensive model that takes into account authentic water management and climate conditions over a 24-year period (1990–2014) in the semi-arid region of the Carson Valley in the western USA. Results from their model showed that in seven out of the 24 years simulated, Ag-MAR was applied (during

Table 1
Schematic of managed aquifer recharge (MAR) methods (modified from Dillon, 2005 and Dillon et al., 2009).

(A) Aquifer storage and recovery (ASR) 	Injection of water into a well for storage and recovery from the same well. This method is useful when storage is the primary objective (e.g., brackish aquifers).
(B) Aquifer storage, transfer, and recovery (ASTR) 	Injection of water into a well for storage and recovery from a different well. This method allows for additional water treatment in the aquifer by extending the residence time.
(C) Infiltration ponds 	Diversion of surface water into off-stream basins, allowing the water to percolate through the vadose zone to the underlying unconfined aquifer and ultimately be recovered from a designated well.
(D) Percolation tank/recharge weir 	Dams built on seasonal streams are used to retain floodwater, which percolates through the soil, enhancing unconfined aquifer storage, and is ultimately extracted down valley from a designated well.

(*continued on next page*)

Table 1 (*continued*)

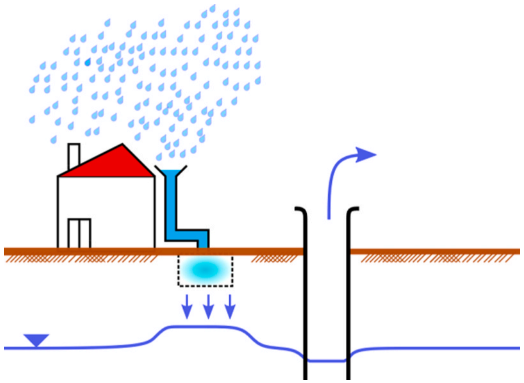
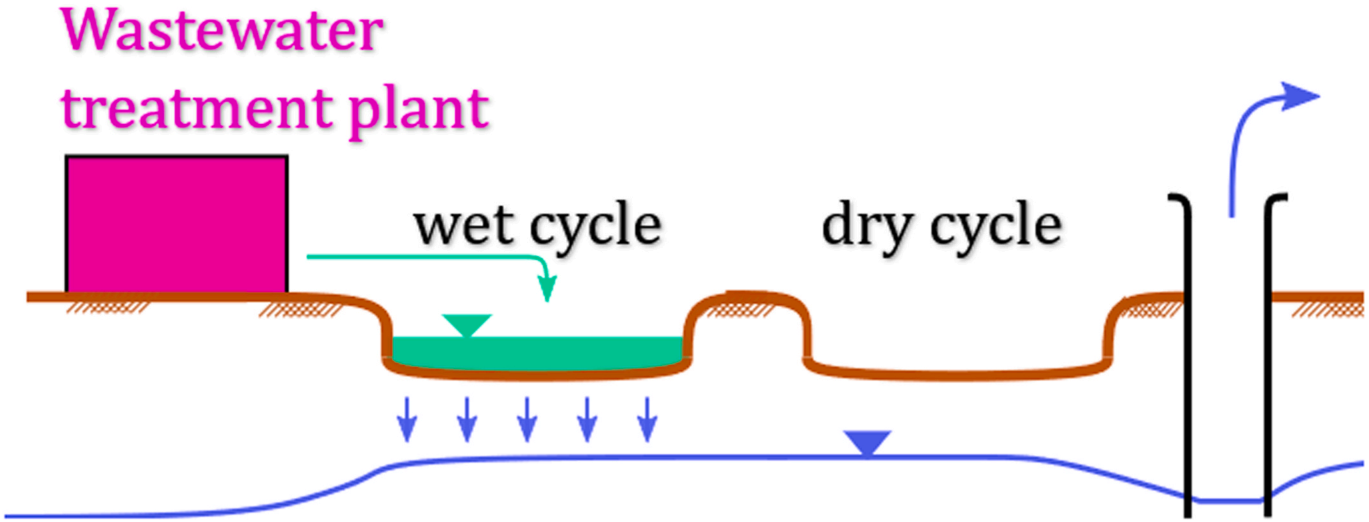
(E) Rainwater harvesting 	Roof runoff is diverted into a well or a sand/gravel-filled cell that allows percolation to the underlying water table and is ultimately collected by pumping from a designated well.
(F) Soil aquifer treatment (SAT) 	TWW is intermittently infiltrated through infiltration basins to facilitate nutrient and pathogen removal in the passage through the vadose zone for recovery by wells after residence in the unconfined aquifer.

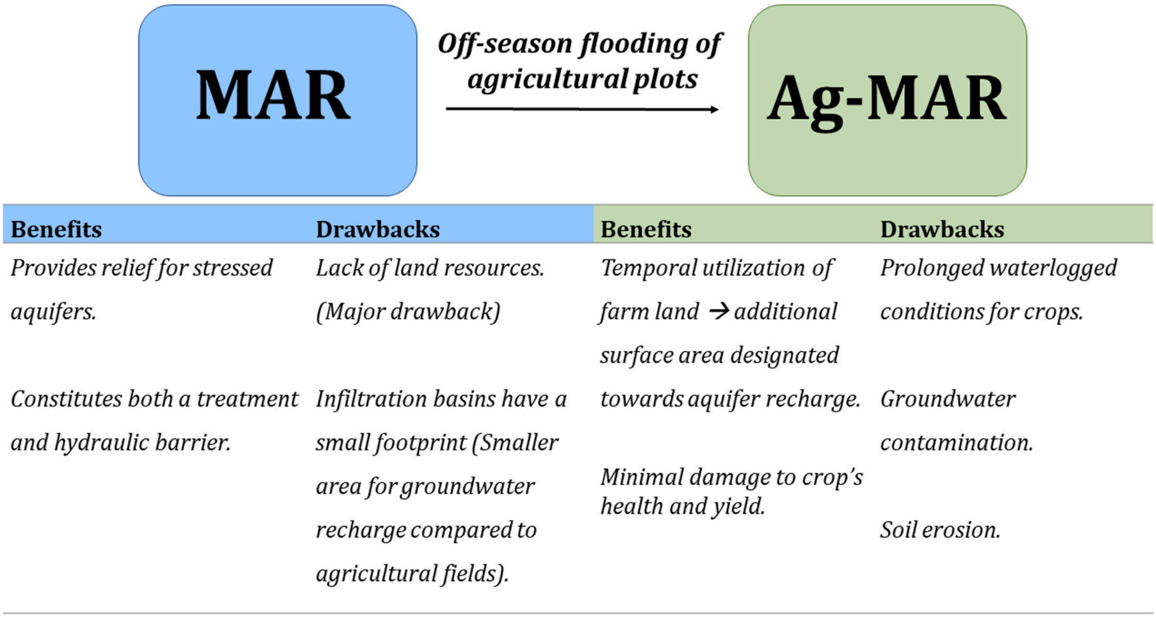
Fig. 1. Agricultural managed aquifer recharge (Ag-MAR) in an almond orchard in California.

these years, excess surface water was available for Ag-MAR utilization). This simulation produced elevated groundwater levels, by 5.5 m, that remained 1.5–2.5 m above the "no Ag-MAR" water level scenario for up to six years after an Ag-MAR recharge event. These results constitute a 9–12% increase in total recharge. Using their model, the authors have also demonstrated that in a single year of applied Ag-MAR, the water table rose by 2.5 m and remained as such for three years, despite a drought event at the time. It is also important to note that the improved groundwater sustainability increased crop water consumption, which is believed to increase crop yields.

Kourakos et al. (2019) used a large-scale, integrated groundwater-surface water model to evaluate the potential benefits and consequences associated with adopting different Ag-MAR practices in California's Central Valley, one of the most agriculturally productive regions in the world, hosting a wide variety of crops. They evaluated four different spatial recharge scenarios for winter Ag-MAR over an 88-year simulation period (1921–2009). The model predictions indicated that Ag-MAR recharge elevated groundwater levels by up to 6 m in the first year of recharge. A maximum water table level rise of 27.4 m was observed at the end of the recharge period (after 80 years of recharge) in some of the scenarios. These long-term large-scale simulations aid in evaluating aquifer sustainability and groundwater extraction in order to provide further improvements in water resources (Niswonger et al., 2017). They also help to illustrate how different Ag-MAR scenarios and parameters may affect the outcome of an Ag-MAR project (Kourakos et al., 2019).

To date, few Ag-MAR field pilot studies have been carried out. Bachand et al. (2014) examined the infiltration rates of floodwater in farmland in California's Kings River basin. The floodwater was diverted from the Kings River into a 4-km^2 Ag-MAR test area with a groundwater depth as great as 45 m or more below land surface (Harter et al., 2005). The Kings River Basin, located in a semi-arid Mediterranean climate, suffers from severe, chronic groundwater overdraft and is subject to flooding during the winter rainy season. Thus, winter Ag-MAR may solve both issues simultaneously (mitigating floods via floodwater diversion to Ag-MAR plots while recharging the stressed aquifer). The experiment was conducted on three different crops (alfalfa, pistachio, and vineyards) and fallow land (prior to spring planting). The tested soils, typical to the region, included fine sandy loam, loamy coarse sand, loamy sand, and pond fine sandy loam. Most are considered to have limited infiltration rates (Dahlke et al., 2018b). An average infiltration rate of 10.7 cm/day was measured, with coarser soils having an infiltration rate of 40 cm/day and the finer soils 6.8 cm/day. Seasonal accumulated water applications ranged between 0.5 and 3 m, for 10 and 34 days of flooding, respectively. Based on soil water capacity estimates, recharge water reached vadose zone depths of 3–6 m, and, in one instance, even 36 m. The higher volumes are positively correlated to the number of days flooded. For an agricultural field inundated for about 30 days (resulting in 2–3 m of applied water), averaging 0.3 km^2 in size, these infiltration rates yield a direct recharge of between 0.55 and 0.86 million cubic meters. Groundwater quality results indicated an elevation in several chemical constituents compared to the diverted storm water, mainly in nitrogen concentrations. Ammonium and nitrate concentrations increased from approximately 0 to 14 mg/L and 0–17 mg/L, respectively. It is very important to note that none of the crops displayed root damage or yield loss due to the controlled flooding (Bachand et al., 2016).

Dahlke et al. (2018a) evaluated the suitability of alfalfa fields for aquifer recharge in an on-farm Ag-MAR setting. Two experiments were conducted, one at the UC Davis plant research farm, and the other in



Benefits	**Drawbacks**	**Benefits**	**Drawbacks**
Provides relief for stressed aquifers.	*Lack of land resources. (Major drawback)*	*Temporal utilization of farm land → additional surface area designated towards aquifer recharge.*	*Prolonged waterlogged conditions for crops.*
Constitutes both a treatment and hydraulic barrier.	*Infiltration basins have a small footprint (Smaller area for groundwater recharge compared to agricultural fields).*	*Minimal damage to crop's health and yield.*	*Groundwater contamination.*
			Soil erosion.

Fig. 2. Major benefits and drawbacks of managed aquifer recharge (MAR) and agricultural managed aquifer recharge (Ag-MAR).

California's Scott Valley. Alfalfa is a viable contender for agricultural groundwater recharge for several reasons: (1) it fairs well when flooded in cool conditions (Undersander et al., 2011); (2) it is widely grown in California (most of which is under flood irrigation (Schwankl and Prichard, 2003), and thus, many fields are likely to have the soil and underlying aquifer conditions suitable for recharge, as well as proper infrastructure to transport water from rivers to recharge fields); and (3) it is a nitrogen-fixing plant (minimal application of fertilizer is required, resulting in reduced nitrate leaching to the groundwater) (Walley et al., 1996). The experimental flooding events during the winter months demonstrated minimal yield loss in highly permeable soil. One major concern was the risk of prolonged anaerobic conditions due to waterlogging, which can cause root damage. Although reduced oxygen concentrations were observed in the root zone during the flooding events, the soil promptly returned to its pre-flooded condition in a matter of several days following the halt in water application. A groundwater table rise was observed within 11–18 h from the moment the water was applied, meaning that the water percolated through the 7.6-m vadose zone in less than 24 h. This rapid infiltration and quick restoration of aerobic conditions are due to the high soil hydraulic conductivity present in this site (Dahlke et al., 2018a). Additionally, the results show that the water application (in conjunction with precipitation) raised the groundwater table in the Scott Valley site by 1.8 and 1.4 m during the off-seasons of 2014 and 2015, respectively. In these studies, Ag-MAR was shown to be beneficial to aquifer recharge while minimizing the damage to the crop's health and yields.

Current Ag-MAR projects are taking place both at research facilities and at sites where growers are willing to participate in off-season deliberate flood irrigation of their fields (Dahlke et al., 2018a; Kourakos et al., 2019; Niswonger et al., 2017). In order to evaluate the long-term benefits and impacts of Ag-MAR on groundwater supply and aquifer sustainability, additional on-farm studies are essential. In this regard, collaboration with agricultural land owners for testing different Ag-MAR strategies, including different types of source water, water application regimes, monitoring tools, soil, and crops, is essential to assess the feasibility of applying Ag-MAR in future large-scale operations.

3. Soil aquifer treatment (SAT)

3.1. SAT process, global perspectives, and benefits

A unique MAR technology that utilizes treated wastewater (TWW) as source water is known as soil aquifer treatment (SAT). SAT is a wastewater reclamation/reuse technology that improves wastewater effluent to high quality recharged effluent through soil passage (Sharma and Kennedy, 2017). Thus, it can constitute a vital component in an indirect potable reuse system (Amy and Drewes, 2007). A schematic of a SAT system is shown in Table 1 (F). The SAT process is commonly applied for further treatment and reuse of primary, secondary, or tertiary effluents originating from wastewater treatment plants (WWTPs) (Kazner et al., 2012). In the conventional SAT setup, the effluent exiting the WWTP is intermittently discharged (flooding and drying cycles) for infiltration through designated infiltration basins (Dillon, 2005). The intermittent operation scheme and the water quality are the two characteristics of SAT that distinguish it from most MAR methods. Flooding and drying cycles are crucial to SAT operation as they enable the aeration of the soil underneath the SAT basin and maintain steady infiltration rates (Negev et al., 2020). During the treatment process, effluent percolates through the vadose zone while being subjected to contaminant removal mechanisms, such as physical filtration, biodegradation, adsorption, chemical precipitation, ion exchange, and dilution (Fox et al., 2001). These processes are most effective in the near-surface layer of the vadose zone, which contains the higher oxygen concentrations necessary for biological treatment (Icekson-Tal et al., 2003). After a residence time ranging from a few months to a year, in both the unsaturated and saturated zone, the effluent is reclaimed via recovery wells from the underlying unconfined aquifer (Dillon et al., 2009; Oren et al., 2007). The long residence time aids in disinfecting the effluent by efficient removal of harmful pathogens (Elkayam et al., 2018). Ultimately, the reclaimed water is suited to a variety of applications, including groundwater recharge (e.g., prevention of seawater intrusion), agricultural and landscape irrigation, recreational use (lakes and estuaries), aquaculture, and industrial purposes (e.g., cooling) (Huertas et al., 2008). A SAT infiltration basin can be seen in Fig. 3.

SAT is a globally practiced aquifer rehabilitation technique (Table 2). Israel possesses one of the largest wastewater treatment facilities worldwide (Dan Regional Reclamation Project, aka Shafdan), accompanied by SAT facilities capable of very high effluent loading rates (around 120 Mm^3/year (Negev et al., 2020)) (Aharoni et al., 2011; Icekson-Tal et al., 2003). The United States hosts many SAT facilities (e.g., in Arizona, California, Colorado, Florida, Massachusetts, Michigan, Montana, New Jersey, New York, and South Dakota) (Crites et al., 2006; Sharma and Kennedy, 2017). Some examples of other SAT practitioners worldwide include Spain (Escalante et al., 2009), Belgium (Van Houtte et al., 2012), South Africa (Tredoux et al., 2012), and Australia (Dillon et al., 2006). A more detailed list of SAT facilities can be found in Table 2.

SAT systems are a year-round operation. They are based on natural processes, easy to operate, and offer water storage in periods of low demand and water extraction in periods of high demand (Aharoni et al., 2011). In addition to the MAR advantages previously mentioned, SAT offers: (1) improvement in the physical, chemical, and microbial quality of recharged water through vadose zone filtration (efficient removal of organics, nutrients, heavy metals, microorganisms, and micropollutants (Aharoni et al., 2011; Wei et al., 2016)); (2) the replacement or support of other treatment processes by providing a robust barrier, reducing the overall cost of wastewater treatment and water reuse; (3) protection of coastal aquifers against seawater intrusion; and (4) promotion of water recycling and water reuse (Sharma and Kennedy, 2017). The latter is

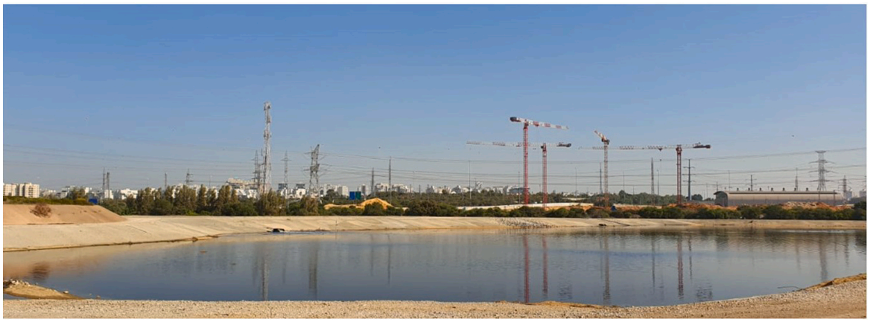


Fig. 3. Soil aquifer treatment (SAT) infiltration basin in the Israeli Dan Regional Reclamation Project (Shafdan) during the wet cycle. Note the nearby construction in the background, illustrating the need for alternative land areas.

Table 2
Selected soil aquifer treatment (SAT) sites around the world.

Country	Location	Hydraulic loading rate (m/year)	Recharge capacity (Mm^3/year)	Inlet effluent	Wet/ dry ratio	Post -treatment	Reference
Israel	Dan region	73–150	115–125	Secondary	0.5	Chlorination or NF	(Aharoni et al., 2011; Negev et al., 2020; Sharma and Kennedy, 2017)
Australia	Alice Springs, Northern Territory		0.6 – 1.3	Secondary	0.33		(Barry et al., 2017)
South Africa	Atlantis		2.75	Secondary		Ion exchange+ chlorination	(Jovanovic et al., 2017; Tredoux et al., 2012)
Belgium	Torreele/ St. Andre		1.95	Advanced treated effluent		Aeration +RSF+UV	(Van Houtte et al., 2012; Van Houtte and Verbauwhede, 2012)
USA	Boulder, Colorado	30.3–48.5		Secondary	0.03		(Sharma and Kennedy, 2017)
	Ft. Devens, Massachusetts	28.8		Primary	0.14		(Sharma and Kennedy, 2017)
	Hollister, California	15.2		Primary	0.07		(Sharma and Kennedy, 2017)
	Fresno, California	13.4					(Crites et al., 2006)
	Phoenix, Arizona	60.6–100	14.6 – 21.9	Secondary	0.75		(Aharoni et al., 2011; Pescod, 1992; Sharma and Kennedy, 2017)
	Scottsdale, Arizona		11.7–39.5				(Aharoni et al., 2011)
	Vineland, New Jersey	21.2		Primary	0.2		(Sharma and Kennedy, 2017)
	Brooking, South Dakota	12.2					(Crites et al., 2006)
	Calumet, Michigan	35			0.14		(Crites et al., 2006)
	Darlington, South Carolina	28					(Crites et al., 2006)
	Lake George, New York	58			0.08		(Crites et al., 2006)
	Orange County, Florida	119					(Crites et al., 2006)
	West Yellowstone, Montana	168					(Crites et al., 2006)

considered a unique benefit of SAT over other MAR techniques. While in many MAR systems, stormwater or floodwater is harvested during wet periods, SAT offers year-round effluent recharge. Many places worldwide dispose of their TWW into the ocean or local streams and rivers (Gunnerson and French, 1996), not realizing wastewater's potential as a resource. In SAT, the reclaimed water is pumped through recovery wells and not directly from the WWTPs; hence, it is no longer characterized as "treated sewage." Additionally, the recharged SAT effluent is typically of high quality, clear, and odorless (Bouwer, 2000; Negev et al., 2017). Thus, SAT can also serve as a platform to educate the public regarding eco-friendly wastewater reuse, helping to gain its acceptability.

3.2. *SAT establishment and operation*

The most critical objective in water reuse projects is the protection of public health and the prevention of environmental deterioration, chiefly when the water being recharged is wastewater. In order to address these concerns, it is of paramount importance to monitor the constituents in the effluent at numerous locations across the treatment process and confirm that said constituent levels are acceptable (Bastian et al., 2012). By optimizing travel time, travel distance, hydraulic loading rate, and operational and redox conditions, SAT is capable of high contaminant removal efficiency (Ben Moshe et al., 2020; Sharma et al., 2012). As in most projects, cost is a driving factor. SAT system costs, including the capital cost of constructing infiltration basins, comprise: (1) pipelines from the WWTP to the SAT site; (2) available real estate designated towards SAT; (3) infrastructure (e.g., extraction wells and pumping system); (4) water quality monitoring systems; (5) basin maintenance; and (6) energy costs (mainly pumping water from extraction wells) (Sharma and Kennedy, 2017). In general, establishing a SAT facility is more economical than that of a conventional above-ground treatment system. Additionally, no chemical intervention or expensive treatment units are required (Sharma et al., 2012).

For successful SAT operation, it is recommended that the WWTP effluent bound for SAT be of a certain standard. According to the US Environmental Protection Agency (EPA), subjecting wastewater to a minimum of primary treatment prior to SAT application is required for non-potable aquifers. However, to prevent basin surface clogging, a secondary treatment might be necessary and is often recommended. For indirect potable reuse, secondary treatment, followed by disinfection (e.g., ozonation) or coagulation/membrane filtration, is highly recommended (EPA, 2004). Post-treatment following SAT is a common practice. Depending on the use of the reclaimed water, post-treatment may consist of aeration and filtration, adsorption, and advanced oxidation or disinfection by UV or chlorine (Sharma and Kennedy, 2017). The latter aids in ensuring that the water recovered is of high quality, minimizing clogging of the main distribution lines to the designated distribution system (e.g., agricultural irrigation), and serving as a residual disinfectant (Aharoni et al., 2011; Icekson-Tal et al., 2003).

As mentioned earlier, SAT produces high-quality recharged effluent. Chemical, biological, and physical parameters, such as suspended solids, chemical and biological oxygen demand (COD and BOD), ammonia, phenols, organic nitrogen, nitrite, phosphorus, iron, and turbidity, are reduced with great efficiency (Icekson-Tal et al., 2003). Several studies have investigated the fate of organic matter during SAT. Results from several SAT case studies show significant reduction in total organic carbon (TOC) ranging from 66% to 90% (Quanrud et al., 2003). The removal efficiency of dissolved organic carbon (DOC) for secondary effluent ranges from 55% to 94%. Additionally, regardless of the soil type and operating conditions, a residence time greater than 30 days increases the DOC removal efficiency to over 80%. When the residence time is shorter, the removal efficiency varies, ranging from 30% to 90%, depending on the type of influent (Sharma et al., 2008).

Another important biological facet of SAT is the nitrogen cycle. Effluent originating from conventional secondary treatment at the WWTP contains nitrogen mainly as ammonium. During the dry cycle (in between flooding events), oxygen is reintroduced, providing conditions for nitrification (ammonium → nitrate). The formed nitrate is mobilized from within the sediment pores during the next application of TWW to the basin. Denitrification (nitrate → atmospheric nitrogen) occurs during percolation through the vadose zone or during storage in the underlying aquifer when anoxic waterlogged conditions prevail, accompanied by a supply of electron donors and adept bacteria (Miller et al., 2006). Mienis and Arye (2018) examined nitrogen behavior in the profile beneath the Shafdan's SAT infiltration basins, collecting data over 40 years of facility operation. Their study concluded that under aerobic conditions in the infiltration basin, over 90% of organic nitrogen (5–10 mg/L in the effluent) and ammonium (2–10 mg/L in the effluent) was converted to nitrate. Moreover, they found that removal of up to 75% of the total nitrogen took place in the near-surface layer of the vadose zone (within the first 70 cm below ground surface). They concluded that overloading the SAT infiltration system with TWW, containing excess nitrogen, creates an unsuitable SAT system, decreasing the recharged effluents' quality. In order for efficient biodegradation and oxidation of both organic carbon and nitrogen species to occur, it is paramount that aerobic conditions exist in SAT infiltration basins (Goren et al., 2014).

A growing concern regarding TWW is the presence of organic micropollutants that persist throughout the wastewater treatment processes. These include endocrine-disrupting compounds (EDCs), pharmaceutically active compounds (PhACs), and personal care products (PCPs). (Amy and Drewes, 2007) studied the fate of PhACs and EDCs in TWW subject to SAT. In their results, only two out of 15 PhACs were detected after SAT. Additionally, EDCs were removed effectively when subjected to medium/long-term SAT. Caballero (2010) and Tsehaye (2012) studied the removal of 13 selected PhACs in different SAT systems. Their results demonstrate that SAT alone, without pre/post-treatment, has high removal of most PhACs, excluding carbamazepine (which also persisted in the (Amy and Drewes, 2007) study). However, their results also showed that adding ozonation pre-treatment or nanofiltration post-treatment increases the removal of all PhACs dramatically, including carbamazepine.

Pathogen removal is of the utmost importance when implementing water reuse projects. Elkayam et al. (2018) conducted an extensive survey focusing on vadose zone purification performance in the Shafdan's SAT infiltration basins. Their study concluded that SAT has excellent removal abilities of human viruses, viral indicators, antibiotic-resistant genes, and numerous indicator bacteria of human origin. Removal of viruses, coliphage, indicator bacteria and microbial source tracking indicators in the vadose zone exceeded 4, 5, 3, and 3 orders of log-particle count, respectively. Another important aspect of the author's work was the removal of antibiotic-resistant genes during SAT, which constitute an increasing threat to public health worldwide (Berendonk et al., 2015). Their results showed an elimination efficiency greater than 2 orders of log-particle count for targeted antibiotic-resistant genes. Moreover, they concluded that plots irrigated with SAT recharged effluent do not contribute to antibiotic resistance.

Fig. 4. Tillage in a soil aquifer treatment (SAT) infiltration basin in the Israeli Dan Regional Reclamation Project (Shafdan).

A major concern related to SAT is the temporal deterioration of hydraulic properties and infiltration rates that are mostly due to biological processes, but also to the intermittent nature of the operation. Mechanical treatment of the soil in the SAT basin, tillage, is a practice exclusive to SAT compared to other MAR systems. Tillage in the infiltration basins allows aeration of the upper soil layer (Negev et al., 2020), by removing the clogging layer (known as "cake"), caused by biological and physical deposition (Aharoni et al., 2011), which alleviates oxygen stress in the vadose zone. Moreover, tillage breaks the surface crusts and vegetation that form on the infiltration basin's surface (Negev et al., 2020). The crust and vegetation are formed by means of algal photosynthesis, which, through chemical processes, changes the soil pH, resulting in the precipitation of chemicals (e.g., carbonate, gypsum and phosphorus). This crust impedes water infiltration and aeration of the vadose zone (Aharoni et al., 2011; Negev et al., 2020). Periodic tillage of the infiltration basin also roughens the basin's surface, subsequently impacting air entrapment. An example of tillage in action is seen in Fig. 4.

3.3. SAT limitations and risks

Limitations and risks that need to be addressed when implementing SAT are: (1) the need for a vadose zone at least 2 m in depth (EPA, 2004), preferably over 5 m (Sharma and Kennedy, 2017), but ideally from 10 to 30 m (Aharoni et al., 2011); (2) the need for specific hydrogeological conditions: high soil permeability for optimal effluent percolation (fine sand, loamy sand, and sandy loam range (Pescod, 1992)); (3) leaching of matter under reducing conditions, resulting in elevated impurity concentrations in recovered water (e.g., manganese (Oren et al., 2007)); and (4) the fact that excessive land area is required for infiltration basins, which may not be available (especially in urban areas) (Sharma and Kennedy, 2017). These limitations and risks are related, either directly or indirectly, to a lack of air penetration in the SAT basin, resulting in anaerobic conditions in the soil. The reduced state hinders oxygen-dependent biological treatment processes, such as nitrification (Ben Moshe et al., 2020), and subsequently degrades the quality of the reclaimed effluents, as observed by Oren et al. (2007).

During winter, SAT basin infiltration rates typically decrease. One reason for this is reduced microbial activity, which is temperature-dependent and thus lower during the cooler winter months. As a result, organic matter decomposition is diminished, causing high accumulation of organic matter in the top soil layer, which impedes infiltration (Nadav et al., 2012). Additionally, climate conditions (i.e., decreased evaporation and moist conditions during the winter) diminish infiltration rates (Orgad, 2017). Another effect of the lower winter temperatures is the increase in water viscosity. As temperature decreases, the viscosity of water increases. For example, a decline in water temperature from 25 °C to 10 °C causes the viscosity of water to rise by more than 30% (in kinematic viscosity: a rise from $0.89 \cdot 10^{-6}$ to $1.31 \cdot 10^{-6}$ m^2/s, respectively). The inverse relation between soil hydraulic conductivity and liquid viscosity (Hillel, 1980) results in decreased flux rates of water infiltrating through the basin (Casanova et al., 2016; Nadav et al., 2012). Slower infiltration rates in the recharge basins, combined with increased inflow of wastewater to the WWTP (that might be due to stormwater transmission to the water system (De Bénédittis and Bertrand-Krajewski, 2005; Joannis et al., 2002)), lead to an increased hydraulic load on existing SAT basins, forcing shorter drying periods in between flooding cycles (Icekson-Tal et al., 2003; Negev et al., 2020). Ben-Moshe et al. (2020) have demonstrated the ramifications of short drying periods. Inadequate air transfer to the soil, followed by anaerobic conditions, was observed during short dry periods. On the other hand, the authors demonstrated that longer drying periods allow for improved oxidizing conditions throughout the soil profile, which result in enhanced effluent treatment. Importantly, the drying period also allows for drying and decomposition of the biocrust on the basin's surface, which as mentioned, impedes infiltration through the SAT basin (Negev et al., 2020).

As noted above, one of the limiting factors for wider SAT application is available land resources with proper hydraulic characteristics, along with proximity to the TWW source. These limitations are even more important during winter, when drying takes longer, the hydraulic conductivity of the soil is typically reduced, and wastewater quantities are increased. Adapting farmlands to enable SAT practice will result in additional SAT infiltration sites and will subsequently reduce the stress on existing SAT basins. This could enable the recharge of all effluent quantities while improving their quality by allowing longer drying periods.

4. Agricultural soil aquifer treatment (Ag-SAT)

A major challenge in executing MAR projects, in general, and SAT projects, specifically, is site selection, e.g., identification of areas suitable for applying groundwater recharge (Crites et al., 2006; Dinesh Kumar et al., 2008; Sallwey et al., 2019). SAT application is often hindered by the lack of infiltration sites in highly sought-after land (as the wastewater source is mostly urban) (Cikurel et al., 2010; Tsangaratos et al., 2017). Therefore, off-season flooding of agricultural plots using effluent from WWTPs, integrating Ag-MAR with SAT (hereafter Ag-SAT), could provide an efficient combination and valuable solution for land availability. To the best of our knowledge, a project using TWW infiltration as a means of aquifer recharge in an on-farm setting (i.e., Ag-SAT) has not yet been undertaken or even explored. Using TWW for Ag-SAT creates several benefits but also generates risks and concerns, which are summarized below:

4.1. *Benefits*

- Decreased stress on freshwater sources, especially in regards to agriculture, which consumes 70% of available freshwater globally (Jaramilo and Restrepo, 2017; Pimentel et al., 2007) .
- Increased water security and availability of irrigation water from recharged TWW (Van Lier and Huibers, 2003).
- Recycling and amendment of soils with organic matter and other nutrients (e.g., carbon, nitrogen, and phosphorous). Compounds present in the wastewater will reduce fertilizer needs (Jaramilo and Restrepo, 2017; Jimenez-Cisneros, 1995; Lal et al., 2015; Van Lier and Huibers, 2003).
- Improved soil properties, such as soil texture and fertility. Irrigation with TWW improves crop yields and broadens the variety of crops that can be grown (particularly, but not limited to, in arid and semi-arid regions) (Jimenez, 2006; Jimenez-Cisneros, 1995).

4.2. *Drawbacks/risks*

- Crop contamination through root uptake of pharmaceutical compounds found in TWW. It is important to note that sandy soils, which are the foundation for SAT basins, present a greater risk for pharmaceutical compound accumulation (Goldstein et al., 2014; Malchi et al., 2014; Shenker et al., 2011).
- Buildup of a clogging layer over time (from the repeated use of TWW) that will reduce infiltration capabilities (Van Lier and Huibers, 2003). In SAT systems, the buildup of a clogging layer could potentially create longer waterlogged conditions for crops, which as detailed earlier, is a major risk.
- Development of hydrophobicity (soil water repellency). This phenomenon affects the uniformity of moisture content distribution, as well as the rate of soil wetting. Hydrophobicity adversely affects agricultural production by creating an uneven distribution of water and nutrients in crop root zone. Moreover, it causes reduced infiltration rates that might lead to enhanced runoff and erosion across the soil surface (Hallet et al., 2011; Wallach et al., 2005).

Dillon et al. (2006) cited a comprehensive list of factors considered specifically for SAT site selection that are paramount for successful SAT implementation, including: (1) land availability; (2) unconfined underlying aquifer; (3) groundwater depth; (4) permeable vadose zone; (5) proximity to source water; and (6) proximity to locations of potential demand. Based on these parameters, some agricultural lands could be suitable for SAT applications in parallel to their crop-production primary use. Additionally, the cost of temporary usage of agricultural land will typically be low, as long as the original use (i.e. crop production) is not significantly affected. An ecological low-cost operation can be

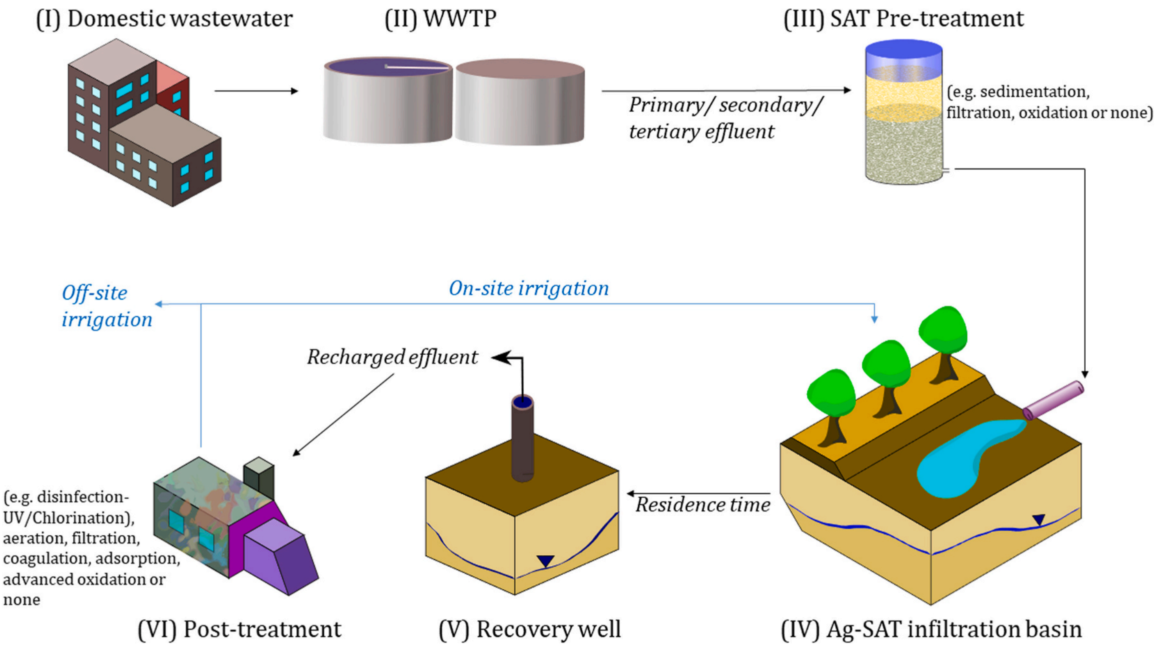


Fig. 5. Schematic of agricultural soil aquifer treatment (Ag-SAT) process stages.

produced by intentional off-season flooding of Ag-SAT sites, and reuse of the recharged water for on-site irrigation. Naturally, off-site irrigation (i.e., regional distribution of the recharged water reclaimed from the Ag-SAT) is a valid option as well. Farmlands that grow crops under a flooded irrigation regime could be ideal Ag-SAT sites, given that the underlying aquifer conditions are suitable for recharge and the overlying vadose zone is permeable and deep enough. In this case, on-season flooding can also be considered.

Fig. 5 demonstrates an example of the Ag-SAT layout. In this process, raw wastewater from domestic facilities is transported for treatment in a WWTP. The effluent leaving the WWTP undergoes SAT pre-treatment. It is important to note that disinfection via chlorination or UV at this stage (Stage III in Fig. 5) is not advised since the biochemical filtration is important. Following SAT pre-treatment (e.g., sedimentation, mechanical filtration, oxidation), the effluent is applied during the off-season via surface spreading (flooding) in agricultural fields modified for SAT (Ag-SAT fields). After a residence time, the recharged effluent is recovered via designated recovery wells. Following recovery, the reclaimed water is treated, depending on the intended use of the recovered water (for example, in the Shafdan, there is no disinfection during post-treatment since the water quality following SAT is satisfactory for unrestricted irrigation (Elkayam et al., 2015)). Finally, the water is distributed for unlimited irrigation. From the bulk operational point of view, the main difference between Ag-SAT and conventional SAT is the location, but in this case, the location may require several unique considerations as discussed below.

Ag-MAR and Ag-SAT are relatively similar procedures at their core. Thus, Ag-SAT site selection can be subjected to similar feasibility or suitability criteria as used for Ag-MAR, such as the SAGBI (O’Geen et al., 2015). Using the SAGBI as a decision support tool for locating potential Ag-SAT sites yields the following factors: (1) deep percolation factor: Ag-SAT soils are typically sandy and thus allow for a high rate of water transmission through the soil (due to high saturated hydraulic conductivity). Furthermore, an Ag-SAT vadose zone’s depth ranges between 2 and 30 m, with most being deeper than the SAGBI-recommended 3 m (to ensure recharge); and (2) root zone residence time factor: As part of the Ag-SAT operation, flooding and drying cycles are essential for aeration. Thus, while implementing Ag-SAT, the intermittent flooding subjects the crops to relatively brief waterlogged conditions that need to be short-lived to avoid harmful anoxic conditions. Additionally, the soil surface condition factor, which considers clogging/formation of crusts, may be treated (if conditions allow) via tillage, thus posing a lower risk. There are unique benefits and drawbacks that need to be addressed when planning Ag-SAT facilities. Obviously, a marked difference between Ag-SAT and Ag-MAR is that the source water in the former is TWW. In other words, when implementing Ag-SAT, agricultural plots are flooded with TWW rather than freshwater. Hence, for satisfactory Ag-SAT results, the crops chosen must be tolerant to waterlogged conditions and TWW’s physicochemical properties.

SAT has demonstrated high efficiency in recharging stressed aquifers while improving the chemical, biological, and physical qualities of the recharged TWW. The utilization of wastewater as a resource is crucial for developing sustainable systems and preventing future catastrophes (Bouwer, 2000). Areas currently operating SAT (see Table 2) have the potential to modify their schemes or expand them by adopting Ag-SAT as a complementary resource. Since minimal additional infrastructure is required, there may be economic incentives for farmers and landowners to adopt Ag-SAT. Endorsing the Ag-SAT technique, especially in arid and semi-arid lands, is a promising ecological solution for providing relief from aquifer stress and overdraft. For Ag-SAT to become a real possibility, a great deal of research and regulatory work is necessary, ranging from small scale laboratory experiments to large scale field tests, including numerical modeling and quantitative analyses.

5. Knowledge gaps in the use of Ag-SAT systems

Ag-SAT may be categorized as a specific case of SAT that uses agricultural plots as infiltration basins, and simultaneously as a specific case of flood irrigation that uses TWW during the off-season. Considering that the agricultural field provides a temporary infiltration basin during the off-season, Ag-SAT can serve as a supplementary infiltration basin to a conventional SAT system when regular SAT basins are nearing their capacity. However, in some cases, Ag-SAT may even be executed during the irrigation season as part of flood irrigation. Ag-SAT may also be considered in rainfed agricultural plots. In the following, we discuss some of the concerns that, in our view, are important to address when considering Ag-SAT.

Naturally, most of the scientific, engineering, and agronomic knowledge regarding Ag-SAT would come from these two parent technologies (SAT utilizing agricultural plots as infiltration basins and flood irrigation using TWW during the off-season). Gaps, however, may exist where differences between the two are wider. While the potential benefits from Ag-SAT are clear (as listed above), there are several risks and drawbacks that still need to be explored. In the following, we discuss several of these knowledge gaps, and where possible, provide an avenue for their closure.

5.1. Agronomic and physiological concerns

Irrigation using TWW has been explored by many researchers (e.g., Assouline and Narkis, 2013; Duran-Alvarez and Jimnez-Cisneros, 2014; Goldstein et al., 2014; Hamdy, 1992; Malchi et al., 2014; Wallach et al., 2005; Zavadil, 2009; Zolti et al., 2019). A wide range of concerns and their ramifications have been studied, including water quality, impact on soil properties, impact on plants, and soil health. Salinity, sodicity, and boron toxicity are three concerning examples. In Ag-SAT, plots would be flooded with TWW that may be somewhat lower in quality than the tertiary treatment standard that is currently recommended (Lakretz et al., 2017).

5.1.1. Concerns related to off-season flooding

As with Ag-MAR, the flooding of agricultural plots in Ag-SAT is expected to take place during the winter, outside of the regular irrigation season (Kocis and Dahlke, 2017; Niswonger et al., 2017). When flooding agricultural land with water for groundwater recharge, a major concern is the creation of waterlogged conditions in the crop’s root zone. While for Ag-MAR, which often uses diverted excess streamflow created from major rainfall events, this concern is (apparently) less of an issue on fallow land or dormant perennial crops (Bachand et al., 2014), Ag-SAT involves water of lower quality (TWW) that is often characterized by a higher microbial oxygen demand (elevated biological oxygen demand, BOD levels) (Likens et al., 2009), which may create depleted oxygen levels in the root zone much quicker than during flooding with oxygen-rich water. Hence, in order for Ag-SAT to become a valuable MAR method, it is important to determine the functionality of root systems and the associated microbial environment in non-dormant crops after a series of TWW flood events. It should be noted that Ag-SAT, like in regular SAT operation (Table 2) is likely to involve short flooding events or intermittent flooding (i.e., pulsed flooding events). This operation scheme is aimed at making oxygen available for biochemical treatment processes (Goren et al., 2014). This is in contrast to recent Ag-MAR experiments that tested longer flooding durations in dormant perennial crops (e.g., winegrapes, alfalfa) (Bachand et al., 2014; Dahlke et al., 2018a). Intuitively, we presume that the concern that using TWW for Ag-SAT will create waterlogged, anoxic conditions in the root zone is more relevant in warm regions where crops are non-dormant or semi-non-dormant.

5.1.2. Concerns related to flooding plots that are normally drip or sprinkler irrigated

As water scarcity is a global concern, irrigation by water-saving technologies (such as drip and sprinkler irrigation) has increased at the expense of flood irrigation (Chai et al., 2014; Schaible and Aillery, 2017; Yadav et al., 2013). One of the main characteristics of drip irrigation is a limited wetted area and consequently, a root zone with relatively low volume. The root distribution properties are greatly influenced by the moisture pattern (i.e. the wetted "bulb" under the irrigation device) that depends on the type of soil, the amount of irrigation water, and the dripper discharge rate (Elaiuy et al., 2015; Reddy et al., 2018). Flooding, especially with TWW, might lead to "re-shaping" of the root zone due to the combined dramatic changes in wetness distribution and water quality.

5.2. Soil quality concerns

Another major facet of Ag-SAT is the potential impact on soil properties. Several potential adverse effects may arise from the practice, including soil degradation, and changes in soil structural stability and associated physical properties, such as lower hydraulic conductivity and higher water repellency (Levy et al., 2011). If drip or sprinkler irrigation is used to recharge TWW, the soil properties are likely to change only in specific locations (e.g., the zone of influence around the drip emitter). On the other hand, in Ag-SAT, the entire surface area is flooded, and therefore, the zone of influence covers the entire soil surface.

5.2.1. Concerns related to nutrient and salt leaching below the root zone

Flood irrigation is associated with high water fluxes, compared to natural recharge (precipitation-driven) and efficient (i.e., drippers, sprinklers) irrigation-induced fluxes. This means that salts and minerals (including plant nutrition minerals) are likely to be leached from the profile (Kovda et al., 1973; Zaman et al., 2018). Although this effect may be perceived as negative in terms of fertilizer loss and groundwater contamination-salinization, it is also beneficial in terms of salinity control (leaching of salts from the root zone that may otherwise be harmful to crops), which is paramount in arid and semi-arid regions (Carter, 1975). Special attention should be given to unique minerals and contaminants that may become mobile under reducing conditions (e.g., manganese (Oren et al., 2007)).

5.2.2. Concerns related to organic matter accumulation

Irrigating soils with TWW is known to alter the soil properties (Levy et al., 2011). This is due to several processes related primarily to the accumulation of organic matter in the soil profile (Duran-Alvarez and Jimnez-Cisneros, 2014). TWW bound for SAT has a typical total organic carbon (TOC) concentration ranging between 10 and 30 mg/L (Quanrud et al., 2003). It is worth noting that enrichment of the soil with organic matter is not necessarily a drawback, and for less fertile soils, Ag-SAT may serve as an alternative to fertilizer application.

As previously mentioned, SAT has a TOC reduction capability of 66–90%, most of which takes place in the near-surface layer of the vadose zone (about 1–1.5 m depth) within a timespan of several days (Sharma et al., 2008; Wilson et al., 1995). Results from a study on long-term organic matter accumulation in the Shafdan's SAT infiltration basins, conducted by Lin et al., (2008), suggest that after long periods of applying TWW (10–15 years) in SAT basins, a steady-state for soil organic content develops in the top soil layer (top 20 cm).

Accumulation of organic matter is characteristic of fields that have been irrigated for extended periods with low quality TWW (Assouline and Narkis, 2013; Yalin et al., 2017), with either a positive impact (e.g., Jun-feng et al., 2007; Lonigro et al., 2015; Vergine et al., 2017), a negative impact (e.g., Nicolás et al., 2016; Zolti et al., 2019), or no impact (e.g., Bastida et al., 2017; Paudel et al., 2016) on the crop yield. Routine tillage between crop rows in Ag-SAT may be beneficial in terms of improving overall infiltration rates but will most likely be less efficient closer to the crops, where the irrigation emitters are located. Additionally, tillage in the vicinity of the crop may harm the root system. Moreover, it is important to note that tillage between crop rows may be technically complicated to execute. On fallow or idle land, this concern is less of an issue; however, for certain row crops that require the preparation of soil beds, Ag-SAT could substantially delay field preparations.

Furthermore, accumulation of organic matter in Ag-SAT plots, due to TWW irrigation, accompanied by an increased wetness regime in the soil profile, due to TWW flooding, might shift the organic matter cycle towards less degradation (less oxic and more anoxic/reducing environments that do not enable full decomposition of solid and particulate organic matter (Boyd, 1995)). The reason is that moister soils may have a higher dissolved organic matter concentration, specifically solid and particulate organic matter (FAO, 2005). Nevertheless, the questions of crust formation, organic matter dynamics, and impact on soil hydraulic properties need further exploration.

5.2.3. Concerns related to soil hydrophobicity

In some soils, prolonged TWW use for irrigation results in soil water repellency (Wallach et al., 2005). It is predicted that hydrophobicity is likely to occur following Ag-SAT. This is due to the probable sandy nature of Ag-SAT soils and large organic matter loads originating from the surface spreading of TWW. Sand particles are more readily coated by organic matter due to their low specific surface area compared to finer soils (Wallis and Horne, 1992). Arye et al. (2011) studied hydrophobicity levels in the Shafdan's SAT infiltration basins. The authors observed hydrophobicity levels in the SAT basin similar to those in agricultural fields planted on sandy soil irrigated with TWW using drip irrigation. Additionally, the hydrophobicity was exhibited only in the surface soil layer (mainly the top 25 cm). These results are surprising since it was expected that TWW spreading during SAT would demonstrate higher levels of water repellency than water-saving irrigation in sandy soils. The authors attribute these results to the drying and wetting cycles, which might cause hydrophobic particles to detach and dissolve into the soil solution. An additional source of organic matter to the soil that should be considered, specifically in commercial orchards, is leaf defoliation (occurring either annually or biannually). The leaf contribution might be substantial enough to induce hydrophobicity or other concerning conditions related to organic matter accumulation (Section 5.2.2).

5.2.4. Concerns related to the change in microbial population (compared to SAT)

In conventional SAT, the soil profile (and especially the topsoil) is exposed to wetting and drying cycles, along with relatively constant TWW quality. At the same time, the microbial population of a conventional agricultural field has its own characteristics that are related mainly to soil management, irrigation, and fertilizer application regime (Kennedy and Smith, 1995; Li et al., 2018). Ag-SAT is likely to experience shifts between irrigation season operation (i.e., conventional agricultural plot) and off-season flooding (SAT functionality). This change in environmental conditions is expected to create a substantial change in the microbial population, which might impact both organic matter degradation and nutrient uptake (Frenk et al., 2014; Friedel et al., 2000; Zhou et al., 2011; Zolti et al., 2019). The impact of this repeated transition on the soil microbial diversity and, consequently, the bio-geochemical cycle is yet to be studied.

5.3. Groundwater quality concerns

Agronomic and soil quality concerns related to Ag-SAT application were presented above (Sections 5.1 and 5.2). These must be addressed in order to encourage farmers to allow their farmland to be used as a temporary SAT facility, and to quantify the soil-crop damage (if any) for proper compensation and appropriate techno-economic evaluation of

Ag-SAT. However, Ag-SAT should also be viewed in terms of the produced water quality, meaning the health of the underlying aquifer and groundwater within.

5.3.1. *Concerns related to groundwater contamination through TWW irrigation*

Wastewater-based irrigation in agricultural fields may result in the pollution of the underlying aquifer. If an Ag-SAT operation is not managed properly, potential contaminants in the TWW, including organic and inorganic compounds, heavy metals, and pathogens, may proliferate through the aquifer (Gallegos et al., 1999). In addition to the ecological damage inflicted on the aquifer, the distribution of contaminated groundwater poses a major risk to public health, especially if the aquifer produces potable water. This concern may be mitigated by proper treatment of wastewater and subsequent production of adequate TWW bound for Ag-SAT (WHO, 2006a). Additionally, monitoring the TWW for quality throughout the entirety of the Ag-SAT process (e.g., exit of the WWTP, Ag-SAT field, throughout the soil profile, before mixing with groundwater, recovered water) is essential.

5.3.2. *Concerns related to leaching of salts, fertilizers and pesticides*

Leaching of salts that are assumed to be correlated to higher water fluxes in the root and vadose zone has a direct impact on groundwater quality. It has been shown that in arid and semi-arid regions, salt accumulates in the vadose zone (beneath the root zone) and diffuses downwards at a relatively slow rate (Gupta et al., 2008; Vengosh and Rosenthal, 1994). Executing Ag-SAT in plots that are usually irrigated using drip/sprinkler systems with freshwater will likely increase soil salinity and sodicity (Assouline et al., 2016). It is expected that flood irrigation is likely to leach these salts from the root zone at a faster rate, which constitutes a benefit in terms of crop production (see 5.2.1 above). While such a mechanism does not introduce new salts to the system, it certainly is a concern in the short term, during the early stages of an Ag-SAT operation (i.e., leaching salts that have been accumulating for long periods of time).

An additional concern is the leaching of fertilizers, specifically nitrogen-based fertilizers, through flood irrigation. This risk is heightened during Ag-SAT since flood irrigation favors nitrate leaching, particularly when the soil is saturated and the texture is coarse (Burguete et al., 2009; Mailhol et al., 2001; Zotarelli et al., 2007). It is important to note that nitrogen-based fertilizers are very common and used globally, as nitrogen is the main nutrient required for plant growth and development (Zhang, 2017). Moreover, TWW typically contains a significant level of nitrogen as well, mainly as organic nitrogen, ammonia, nitrate, and nitrite (Tchobanoglous, et al., 2013; Von Sperling, 2015). Other hazardous contaminants that may leach from the soil profile during flood irrigation, risking groundwater contamination, are pesticides (Arias-Estévez et al., 2008). This risk is heightened during Ag-SAT since pesticide leaching is highest for sandy soils (Perez Lucas et al., 2018). Therefore, safety measurements should be taken to curtail the contaminant intrusion into the groundwater. These may include predictions from the contaminant properties (e.g., mobility, persistence), soil properties (e.g., texture, organic content), mathematical models, and soil and groundwater monitoring and amendment (Aharonson, 1987; Shrestha et al., 2010).

A unique potential wastewater source for Ag-SAT (mainly in Brazil) could be effluents originating from sugarcane plants, also known as vinasse. Vinasse is a high strength wastewater that is typically reintroduced to the fields. Applying the vinasse to the soil is a simple, cost-effective way to introduce agronomic benefits (e.g., increasing yields, improving soil quality, increasing carbon and nitrogen inputs, decreasing fertilizer application, and reducing freshwater needs). Nonetheless, since vinasse is high in potassium, this practice leads to potassium accumulation in the soil and its leaching into the groundwater, with adverse impacts (Bordonal et al., 2018; Ghiberto et al., 2009). To consider the usage of vinasse in Ag-SAT, further scientific exploration is needed.

5.3.3. *Tertiary treatment concerns*

In a conventional SAT facility, a relatively stable ecological system exists with a large microbial community that is capable of degrading most of the organic matter and ammonium present in the TWW (Icekson-Tal et al., 2003; Mienis and Arye, 2018; Miller et al., 2006; Quanrud et al., 2005, 2003). This is achieved after a long operation period (years), assuming a relatively stable water quality and operational regime. In Ag-SAT, the frequency of flooding is expected to be much lower than in conventional SAT. This could have an impact on the microbial community and functionality, related to this community's role in both nutrient uptake by plants (see 5.2.4 above), and organic matter and nitrogen species degradation. It is complicated to predict the microbial structure and functionality, and their dynamics under such an operational regime. This is probably the most unknown factor that will dictate much of the operation and economics of Ag-SAT and, therefore, should be investigated in a series of experiments.

5.4. *Other concerns*

5.4.1. *Health concerns*

Improper regulation and control methods of wastewater-based irrigation could result in the transmission of contaminants to healthy individuals, from both direct and indirect contact (Levy et al., 2011). There are a variety of pathogens (e.g., bacteria, protozoans, viruses) and substances (e.g., pesticides, heavy metals, pharmaceuticals, hormones, etc.) that are of sanitary concern (Jaramilo and Restrepo, 2017; WHO, 2006b). In some cases, the source water utilized in Ag-SAT is not disinfected (e.g., chlorination, UV) in the pre-treatment stage as part of the Ag-SAT process. Thus, the TWW utilized in Ag-SAT poses a heightened health risk. The individuals most intensely exposed to such risks are the farmers and field workers in the Ag-SAT field who may come into direct contact with the TWW (WHO, 2006b). Crops that have fruit in contact with soil (e.g., nuts drying on the orchard floor) may not be suitable for Ag-SAT due to the high risk of bacterial pathogen contamination (e.g., salmonella, E. coli) (Brar and Danyluk, 2018). Since Ag-SAT has not, to date, been tested, the health threats stemming from prolonged TWW ponding and the quality of the produced crops are unclear. Thus, sound risk assessments and proper characterization are required when carrying out an Ag-SAT project. In order to minimize risks and exposure, agricultural workers and researchers should partake in relevant safety measures (Hamdy, 1992) while also confirming that the Ag-SAT operation, and the TWW and crop quality are within the guidelines set by the appropriate regulators.

An example of a such a guideline is Israel's Halperin Committee report (IMH, 2002), regarding the regulatory use of TWW for irrigation purposes. The report states that in order to prevent illness due to TWW irrigation, the placement of a number of "barriers" between the TWW and the crop is recommended, depending on the TWW's quality. These barrier practices may include: (1) removing harmful contaminants in TWW (e.g., through granular filtration, prolonged residence time, dilution with potable water); (2) creating a “disconnect” between the TWW and the crop itself (i.e., by creating a physical distance between TWW and the crop yield); (3) growing crops for non-edible purposes (e.g., energy, building and construction, fiber, renewable biopolymers, specialty chemicals); (4) growing crops that undergo thermal treatment (e.g., wheat); (5) growing crops with non-edible peels (e.g., citrus, banana); and (6) growing crops that are only consumed after cooking.

5.4.2. *Regulatory concerns*

Countries worldwide have enacted different water laws and rights regarding the use of groundwater. In some countries, all water sources are public property and subjected to the jurisdiction of governmental bodies with differing allocation principles (e.g., Israel), while in others, the use of groundwater is privatized to an extent (e.g., United States, Australia, Canada) (FAO, 2006). Examples of legal doctrines to govern groundwater include: (1) absolute ownership (unlimited withdrawal of water below the owner's land, regardless of the impact on other landowners); (2) reasonable use (groundwater withdrawal is limited to a reasonable amount and purpose by the landowner); (3) correlative rights (landowners utilizing a common groundwater source enjoy equal/correlative rights to a reasonable amount of water for reasonable uses on their land); and (4) prior appropriation (the first party to utilize groundwater for beneficial use has the right to continue to do so) (Bryner and Purcell, 2003).

After the SAT/Ag-SAT recharge process, the water quality of the recharged effluent is typically lower than that of the natural groundwater. Thus, preventing the spread of the recharged effluent within the groundwater aquifer is paramount, especially when the underlying aquifer is being used for potable water production. Soil aquifer treatment has been extensively studied and practiced for many years (e.g., the Shafdan started operating in 1977 (Idelovitch and Michail, 1984)). Correct engineering of recovery wells enables the sole extraction of recharged effluents (Bouwer, 2002) from a hydrologically separate zone within the aquifer (Aharoni et al., 2011), thus protecting the underlying aquifer, especially if the treated wastewater applied during SAT is of a secondary treatment level (Crites et al., 2006). The mixing of the TWW applied during Ag-SAT in the underlying hydrological unit needs to be studied for each potential Ag-SAT site location. Additionally, a proper monitoring scheme needs to be planned and executed.

5.4.3. Economic concerns

The adaptation of Ag-SAT by both farmers and SAT operators should be feasible not only with regard to the environmental concerns and water balance, but also to the economic value of the operation. Modifying farmlands to Ag-SAT facilities includes fiscal expenses such as the installation of pipes transporting TWW to the intended plot, a pumping station, recovery wells, mechanical soil preparation, tillage, water quality and soil monitoring systems, and farmer compensation in case of damage to crop health and yield, to name a few. As described above, there are many aspects, both positive and negative, that need to be considered when implementing Ag-SAT. A comprehensive life-cycle analysis (LCA) of Ag-SAT operation should be conducted in general, as well as pilot projects to identify specific concerns and to consider the listed aspects.

6. Summary and conclusions

The increasing stress on water resources, in general, and on agricultural water, in particular, combined with increasing amounts of domestic wastewater, inspired the Ag-SAT concept. Ag-SAT is a specific form of Ag-MAR where TWW is used as floodwater instead of diverted streamflow, rainfall-runoff, or snowmelt runoff. Seemingly, it is a promising approach that holds great potential, especially as land availability for SAT is decreasing and becoming more expensive while TWW volumes are increasing. Nevertheless, as the approach has not been tested and no active Ag-SAT system exists, it is difficult to anticipate how the soil–plant system will respond (both in the short- and long-term) and what the ramifications of Ag-SAT on public health or the environment will be. This manuscript presents the concept of Ag-SAT, and tries to identify the main concerns that need to be addressed before Ag-SAT can be commercially implemented and the factors that need to be monitored throughout its application. These concerns are related to both agricultural and water quality aspects. As Ag-SAT may be categorized simultaneously as a specific case of SAT and as a specific case of Ag-MAR, some of those concerns can be addressed by the available experience and literature. Concerns arise from the few places where the two conflict.

To improve the probability that an Ag-SAT project will be successful, site-crop selection must take into consideration both the crop needs and the water quality treatment needs. It is very important that the crops chosen be: (1) tolerant to waterlogged conditions, that is, crops proven to be able to withstand ponded conditions; (2) able to cope well while (flood) irrigated with TWW; and (3) suited for growth and development on sandy soils (Ag-SAT's preferred soil texture). By doing so, it is predicted that the health and future yield of the crops will not be negatively affected. It is important to note that in cases where Ag-SAT is executed on farmlands with dormant plants (i.e., colder regions) or on fallow land, concerns related to plant tolerance to TWW flooding is of less concern. Additionally, Ag-SAT flooding will be intermittent (i.e., wet and dry cycles) to allow soil aeration, similar to SAT basin operation. Therefore, crop tolerance to ponded conditions is limited to short durations. Additional important aspects are related to the long-term soil and aquifer water quality resulting from an Ag-SAT operation.

We primarily focus on technical concerns that are, in our view, mostly solvable. There are concerns related to public health, and as such, require regulatory action. These are mostly related to the need to irrigate crops with non-disinfected TWW. Therefore, it is suggested that at this stage, Ag-SAT experiments and feasibility studies be done in isolated and dedicated plots, and not in commercial plots.

Pilot tests evaluating the crop and soil response to flood irrigation using TWW are crucial in order to determine Ag-SAT feasibility. Tests could focus on exploring different crops, soils, wet/dry cycles, loading rates (i.e., volumes of TWW applied, measured in m/year), tillage techniques, and climates (e.g., precipitation and temperature). Further, monitoring of soil, pore water, and soil gas before, during, and after Ag-SAT flooding is necessary to examine and oversee the process quantitatively. Monitoring redox conditions, gas concentrations (e.g., oxygen, carbon dioxide, nitrogen species), pH, water analysis (e.g., heavy metals, organics, nitrogen species), volumetric water content, temperature, electric conductivity, and pressure during the Ag-SAT process is needed. The sampling should be comprehensive and take place in different stages of the process, from the planting of the crops and onward, spanning various locations (e.g., WWTP, agricultural plot, groundwater, and reclaimed water) and depths. Since there is no information available on Ag-SAT and its potential impact on the soil, crops, reclaimed water quality, the vadose zone, in general, or the root zone, in particular, experimental insight will shed important light on the developing concept of Ag-SAT and its feasibility.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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