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Review article

Moistube irrigation technology development, adoption and future prospects: A systematic scoping review

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ABSTRACT

Agriculture is the biggest consumer of fresh water in the world accounting for almost 70% of the water use. The burgeoning world population and increased demands to feed the world requires novel technologies that reconcile water consumption and food security. Moistube is a polymeric semi-permeable membrane irrigation technology that is known to improve water use efficiency and boost yields. The technology is relatively new, hence a lack of comprehensive literature regarding Moistube irrigation (MTI) technology warrants empirical investigation of the existing literature. The study performed a systematic review guided by the Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) and the scoping studies methodological framework to compile an evidence-based literature review on Moistube irrigation. The study performed search queries in the following over-arching and comprehensive databases for grey literature: Google Scholar, Science Direct, Research Gate, CAB direct, All Journals, CNKI, FAO, SCOPUS, Web of Science, and UKZN-EFWE. DistillerSR software was used for screening, data extraction and data charting. Article screening retained one hundred and 55 (n = 155) articles. Forty-nine articles (n = 49) and information sources were found to be related directly and indirectly to Moistube. Moistube articles (n = 29, 59%) were from China were the technology originated. A bulk of literature reported Moistube irrigation use in the arid regions of China. The review revealed areas for research enquiry into the subject matter. Future research areas were fertigation performance under MTI, effects of waste-water on MTI nanopore plugging, yield response of industrial crops of economic importance under MTI and soil wetting geometries under MTI. This signified the need to perform further research enquiries into the subject matter to improve literature availability. Moistube irrigation technology has a low adoption rate in Africa with reported use in South Africa and Morocco. The technology has massive adoption potential in arid and semi-arid regions of sub-Sahara Africa.

1. Introduction

Climate change poses the greatest threat to rain-fed agriculture (Smit and Skinner, 2002). Erratic rains have seen a reduction in crop production in several parts of the world and sub-Sahara Africa (SSA), causing food insecurity to the vulnerable population. Irrigation mitigates the adverse effects, however, the irrigation panacea consumes 70% of the earth's freshwater resource (Rost et al., 2008). Novel technologies such as micro-irrigation have been developed to maximise crop production with minimal water usage. The water use efficiencies are estimated to be 95% (Lamm et al., 2012). Subsurface drip irrigation (SDI) is extensively used in arid regions of the world (Lamm et al., 2012) as it minimises non-beneficial water use, i.e. it prevents water losses due to soil evaporation, deep percolation and surface run-off. In addition, Lamm et al. (2012) presented challenges faced by farmers who adopt the technology. For example, due to no visuals, the SDI can be hard to manage since the problems occur underground. Previously subsurface irrigation was achieved using buried ceramic clay pots (Cai et al., 2017). The technique allowed water to migrate through the micropores in the direction of suction. The suction was induced by differential soil water potential.

Irrigation technology has utilised porous media such as ceramic pitcher pots for improved irrigation water use efficiency (WUE) (Cai et al., 2018). Moistube irrigation (MTI) is a semi-permeable porous membrane, and a relatively new technology that simulates the clay pot

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irrigation. The Moistube is an upgraded flexible semi-permeable membrane whose pores are in nano-scale (Kanda, 2019). The technology was developed in China and Jun et al. (2012) did experimental work which proved that MTI had high water use efficiency and asserted its suitability for arid regions. The nanopores are uniformly and densely distributed, as such, high irrigation uniformity is easily achieved (Jun et al., 2012; Fan et al., 2018). Because the technology is relatively new, there is not much empirically investigated literature detailing usage, implantation and adoption across the globe. Adoption rate is high in China's arid and semi-arid regions. In Africa it has only been reportedly used in South Africa and Morocco. This presents a challenge of a lack of longitudinal and cross-sectional data that can be used to perform systematic and meta-analyses reviews.

Evidence-based scoping reviews facilitate exhausting the available literature and identifies potential research for future investigations. It is against this backdrop that the study employed a systematic scoping review to identify the extent to which Moistube irrigation technology use has been adopted. The scoping review sought to provide answers and research gaps from a narrow range of Moistube irrigation literature. The study undertook a systematic scoping review with the aim to identify, group, and synthesize the extent of Moistube use and adoption in irrigation. Performing such exercises highlights possible research gaps that can be exploited for expanding literature around the subject area. In addition, the paper sought to answer the following questions:

i) What evidence is available on MTI advance in the irrigation community?
ii) What are the potential knowledge gaps that can be presented for further MTI research enquiry?

1.1. Brief description of moistube

Moistube irrigation (MTI) technology can be classified as an upgrade of buried clay pot irrigation and porous pipes in terms of the material and size of pores where the latter two are micro-porous (Teeluck and Sutton, 1998; Bainbridge, 2001) while the former is nano-porous. The Moistube is made of a polymeric semi-permeable membrane (SPM) that facilitates moisture movement by soil water potential difference (Yang et al., 2008) and system pressure (Niu et al., 2013). Much like the clay pot counterpart, the Moistube releases moisture at the rate at which the plant absorbs water (Bainbridge, 2001; Zou et al., 2017 & Kanda et al., 2019). MTI uses membrane technology (Petty et al., 1995) with the inner surface of the Moistube closely simulating the vascular plant tissue. With approximately 100,000 nanopores per square centimetre and a pore diameter of 10–900 nm (Zou et al., 2017; Kanda, 2019), the inner membrane capitalise on the soil-moisture gradient for advection (Yang et al., 2008) and it assumes a line source infiltration mechanism during irrigation (Fan et al., 2018).

The water flow mechanism under MTI occurs in two ways, in the presence and absence of system pressure. In the absence of system pressure, the water flow is driven by the soil water matric potential (Yang et al., 2008). In the presence of pressure in the system, the flow is governed by both soil water matric potential and system pressure (Niu et al., 2013). However, the effect of soil water matric potential lasts for about 44 h and thereafter the flow is driven by system pressure (Niu et al., 2017b). The soil water matric potential in driving water out of the Moistube presents an interesting scenario where saline water is used for irrigation since it may occasion reverse flow due to the effect of osmotic potential due to salts (Kanda et al., 2019).

It has been established that Moistube irrigation (MTI) saves water and improves yields and water use efficiency (WUE) in various crops grown China (Kanda et al., 2019). The technology was pioneered in China and most of the experiments have been done there. However, in South Africa, Kanda et al. (2020a) established that the yield and water use efficiency of cowpea under MTI were not significantly different from subsurface drip irrigation. Apart from operational advantages such as low pressure requirement (Kanda et al., 2018), MTI has higher irrigation uniformities than drip irrigation (Zhang et al., 2012). Africa, like China, has diverse climatic conditions and thus, it is expected that MTI will help in expanding irrigated agriculture in the continent and alleviate food insecurity problems.

2. Methodology

The paper adopted the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) framework by Moher et al. (2015) that defined the methods and protocols for literature reviews. Similar studies (Arksey and O'Malley, 2005; Lam et al., 2015; Moffa et al., 2019) adopted the framework in the fields of public health and medicine. This offers an opportunity to extend the methodological framework to domains such as agriculture and engineering. A systematic scoping review was employed in order to map the broad literature that answered various research questions pertaining to MTI. The PRISMA-P framework outlines the phases involved in mapping the literature, namely (i) eligibility criteria and information sources, (ii) search strategy, (iii) data management, (iv) selection process, (v) Strength of evidence assessment, and (vi) outcomes.

2.1. Eligibility criteria and information sources

The study utilised all information found on the internet regarding Moistube. Considering that MTI is a relatively new irrigation technology, reports from publications, conference proceedings, news releases, seminar papers, post-graduate research theses, and retailer and manufacturers websites were utilised for the study. The study did not place emphasis on publication date and searched the following databases for information: Google Scholar (https://scholar.google.co.za/), Science Direct (https://www.sciencedirect.com/), Research Gate (www.researchgate.net), CAB direct (www.cabdirect.org), All journals (www.alljournals.cn) and CNKI (www.cnki.com.cn), SCOPUS (www.scopus.com), and Web of Science (mjl.clarivate.com). The following websites were visited for information sourcing: Moistube (http://www.moistube.ae/desert.html), FAO (http://www.fao.org/home/en/), and UKZN-EFWE (http://efwe.ukzn.ac.za/Libraries/ResearchSeminars/). The databases were selected based on their comprehensive and over-arching nature in terms of information archiving.

2.2. Search strategy

In order to access the relevant information without bias, broad search terms were used. The search terms associated with Moistube, semi-permeable membrane flow and location were the three key phrases used to access information from the databases. The search terms were coupled with the use of the "**AND**" and "**OR**" Boolean operators. The search queries were typed into the Databases (DB) and each respective DB returned a search value as summarised in Table 1. In some instances, the search queries involved the singular "moistube" word. The literature search was done in March 2019 to January 2021.

2.3. Selection process

The screening process was aided by the use of DistillerSR© software (Evidence Partners, Ottawa, Canada). The software facilitates article screening via titles, abstracts and citations, just to mention a few. The study employed a two-step screening process based on article titles and the second stage screening process was based on abstracts and keywords. Our study adopted an inclusion criteria that was related to: location, type of crop under irrigation, water conservation, porous pipes, and semi-permeable membrane. Because Moistube technology is relatively new and there is minimal empirical literature, the authors used their discretion to assess and categorise the articles into the inclusion-exclusion

Table 1. Summarised results from DB searches.

Database	Number of articles returned from search queries
Web of Science	10
SCOPUS	22
UKZN-EFWE	1
CAB Direct	0

Table 2. Inclusion-exclusion criteria applied for relevance screening.

Inclusion	Exclusion
- Articles published in English	- Articles not published in English
- Original research in a peer-reviewed journal	- Articles from Predatory journals
- Full articles that could not be retrieved	
- Articles that described porous pipes, pitcher pots use in permaculture	
- Articles relating to line source wetting patterns	- Articles with insufficient methodologies
- Moistube articles with English abstracts	
- Conference proceedings - MSc and PhD dissertations	

groups. It is worth mentioning again that the technology has been exclusively employed in arid and semi-arid agriculture regions of China hence, the bulk of the information was found in Chinese databases (CNKI and All Journals). The main articles retrieved were in Chinese with English abstracts, this however, contradicts with Badger et al. (2000) who opined that an abstract does not give the required scope and depth of the article, however, the scarce MTI literature prompted the study to capitalise on abstracts. Table 2 summarises the inclusion-exclusion criteria applied to screen for relevance.

The study classified predatory journals as those that did not identify an editorial board and appeared on Beall's list of predatory journals (Beall, 2011; Xia et al., 2015). Duplicate checker quarantined 4 out of 154 resulting in 150 unique citations. Thereafter, screening 150 articles using abstract and title, 52 articles met the inclusion criteria. Further examination resulted in articles that exclusively discussed Moistube irrigation technology use. Figure 1 (PRISMA flow chart) summarises the inclusion-exclusion phases.

2.4. *Strength of evidence assessment*

The literature review employed a strength of evidence approach for agricultural sciences prescribed by Thomas et al. (2019) (Table 3). The grading follows that substantiated and documented research is given a *high* score, whereas a *moderate* score is assigned to partially substantiated studies and studies with conditional conclusion. Opinion papers are assigned a *low* score and none-evidenced based research are ungraded (Thomas et al., 2019). The selected studies after screening are summarised in Table 4 together with the strength of evidence score.

3. Results and discussion

3.1. *Data charting and extent of adoption of moistube irrigation*

Thirty-one studies in the inclusion criteria were from Asia (Table 4). Studies directly relating to Moistube (n = 32, 54%) were from China

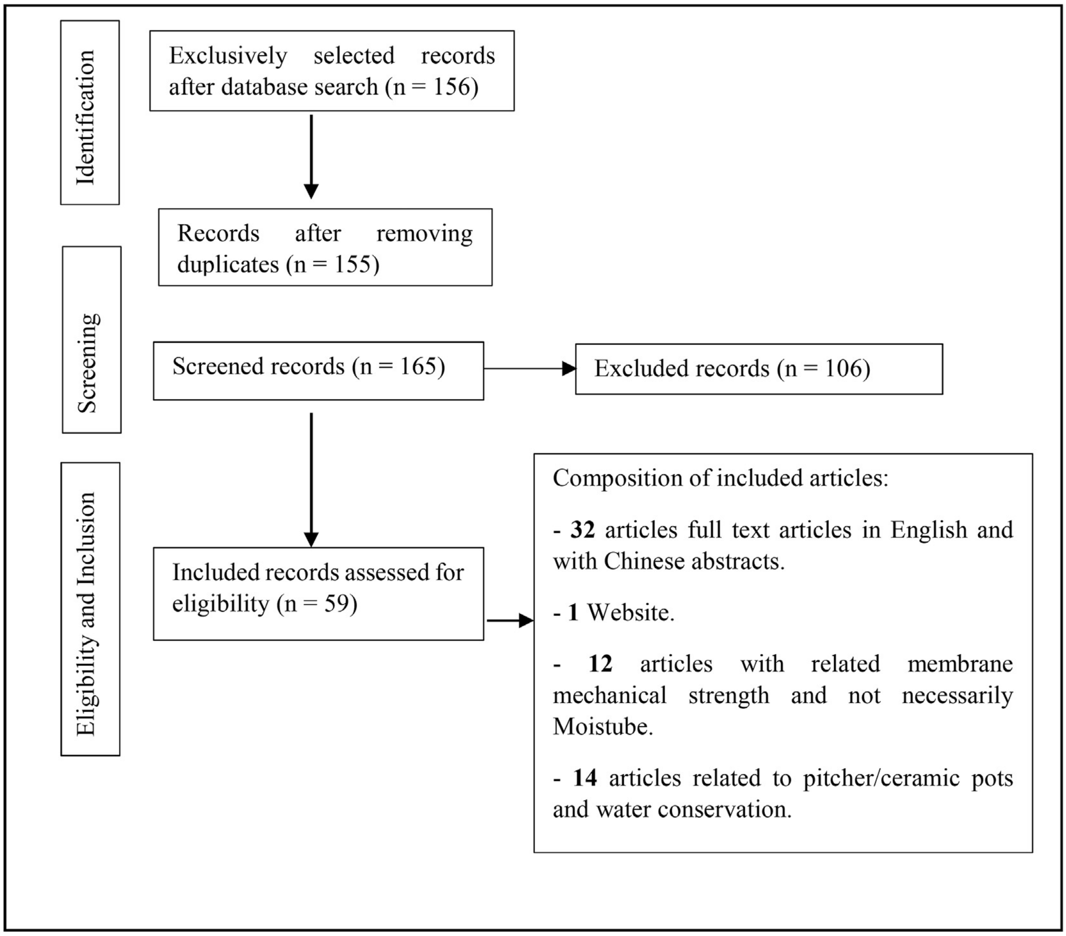

Figure 1. PRISMA flow chart of the selection criteria employed to chart Moistube literature.

Table 3. Strength of evidence grading (adapted from Thomas et al., 2019).

Strength of evidence	Type of agricultural research	Study design	Study type	Evidence
Strong (I)	Applied research, adaptive/farm level research, strategic research, systematic reviews and meta-analyses	Experiments, field trials, systematic reviews	Experimental/structured review	Substantiated
Moderate (II)	Case studies/reviews, modelling/simulation	Case studies, narrative reviews, simulations	Observational	Partially substantiated
Low (III)	Opinion papers, conference papers, workshop papers	Qualitative research, opinion papers, reports of expert committees	Descriptive	Unsubstantial, qualitative analysis and opinions
Very low (IV)	N/A	N/A	N/A	N/A

where the technology emerged from. Africa as represented by Morocco and South Africa (n = 10, 17%) was a minority. Ceramic or porous or pitcher pots (n= 6, 13%) were reported in Asia again (Thailand, Pakistan, China and India). It is worth stating that the data extraction and charting was performed during the period March 2019–January 2021.

3.2. Further discussion on moistube and potential research gaps

The authors further discussed the MTI literature as guided by the research questions flagged in the introduction and the emerging themes (Figure 2). The following sections offer a discussion that flags potential research gaps that warrant empirical investigations.

The literature network provided themes that are dominant under MTI and ceramic pitcher pots. The dominant theme was centred on infiltration and soil moisture, which signified how a significant amount of research has been focused on understanding soil water dynamics under MTI. Another dominant theme was on pressure head. There exists literature around MTI discharge under positive pressure. This however highlighted the need to investigate MTI under negative pressure. Dirwai et al. (2020) investigated MTI negative pressure discharge.

3.2.1. Yield response of various crops under moistube irrigation

A total of 12 out of 44 (n = 12, 27%) studies related to yield response and WUE under MTI. MTI has been used extensively for vegetable and maize production in arid and semi-arid regions of China. For instance, Lyu et al. (2016) experimentally assessed the effects on greenhouse-grown tomato yield of MTI lateral placement depth. Lyu et al. (2016) reported an increase in tomato crop biomass and an increased WUE of 103.4% as compared to that of drip irrigation. The study further revealed that MTI had a capacity to improve water saving by 38%. This evidence-based literature asserts MTI suitability for adoption in the arid sub-Sahara regions.

Xue et al., (2013) undertook a comparative study between MTI and sub-surface drip irrigation on tomatoes and asserted equal tomato yield per unit area under MTI and sub-surface drip, however, MTI recorded an improved WUE of 60.42 $kg.m^{-3}$ whereas drip irrigation had a WUE of 53.33 $kg.m^{-3}$ Similarly, Niu et al. (2017) investigated the effects on greenhouse tomato yield of MTI lateral placement depth and solute movement in vadose zone. In their experiment Niu et al. (2017), buried the MTI lateral at three different depths of 10 cm, 20 cm, and 30 cm. The study revealed that placement depth influenced soil water and solute movement, this subsequently impacted the dominant root zone density region of the tomato plant. Shallow burying depth allowed for optimal tomato growth in solar greenhouses.

Zhang et al. (2017) comparative study reported a low corn yield under MTI as compared to SDI. However, the winter wheat yield remained constant over two growing seasons. Kanda et al. (2020) carried out a comparative experiment to determine effect of MTI and SDI irrigation on yield response of cowpea. The study was carried out in Pietermaritzburg, South Africa, a humid subtropical climate. The study reported a no significant difference ($p > 0.05$) in yield between the MTI and SDI. MTI has been extensively used for vegetable production in the arid regions of China.

Guo et al. (2017) investigated the effects of lateral placement depth and applied pressure on yield response of onion production under greenhouse conditions. The study revealed that applied pressure had no significant impact on yield, whereas the placement depth contributed to difference in yield. A lateral buried at 0.4 m produced high yield compared to a lateral buried at 0.7 m. Deep buried laterals promote deep percolation hence minimising plant available water. Onion has a shallow and poor laterally distributed rooting system (approximately 0.3 m) (Thorup-Kristensen, 1999; de Melo, 2003), hence shallow buried MTI laterals provide optimal plant growth. This therefore implies that the crop root characteristics is important in the design of MTI. Tian et al. (2016) assessed sunflower growth under MTI and reported a significant increase in yield.

Potential research gaps exist in the fields of crop production under MTI in Africa. Climate change has affected rainfall availability and thus research on the benefits around MTI for vegetable production is critical in understanding the potential benefits proffered by MTI in the arid regions of Africa. The climate variability in Africa presents a non- “one size fits all scenario” i.e., North Africa and Southern Africa are widely arid regions (Figure 3) with potentially high evaporative demand environments, thus adoption of buried water-saving technology provides optimum farming conditions.

3.2.2. Soil wetting geometry

A total of 8 out of 44 (n = 8, 18%) studies related to soil water dynamics under MTI and ceramic pitcher pots. The soil wetting geometry determines emitter placement depth (Dabral et al., 2012). Sub-surface emitters can be classified as point source or line source emitters. Sub-surface drip irrigation when modelled in a 3 dimensional flow is a typical example of point source water application (Patel and Rajput, 2008; Elmaloglou and Diamantopoulos, 2009). Moistube can be classified as a line source emitter which can be modelled as 2-dimensional flow problem. To achieve uniform irrigation and optimal fertigation in sub-surface irrigation, lateral spacing and placement depth are the main drivers (Kandelous and Šimůnek, 2010). It is imperative that an optimum placement depth is maintained since deep-buried conduits will facilitate deep percolation and limit water and nutrients availability to plants (Dukes and Scholberg, 2005; Kandelous and Šimůnek, 2010). In the case of MTI under external pressure, deep buried MTI lateral will also promote deep percolation. Niu et al. (2017) performed a study that assessed the effect of placement depth on soil water dynamics for greenhouse-grown tomatoes. The preferred continuous irrigation (CI) technique provided by Moistube prevented soil salinization. Furthermore, the study revealed varying soil moisture patterns in each respective placement depths of 10 cm, 20 cm, and 30 cm. Soil texture also determines the infiltration capacity under MTI. The infiltration effect of vertically placed Moistube (MTI tubing placed in the vertical plane) under different heads (1 m, 1.5 m, and 2 m) and different soil types namely; sand, sandy-loam and red

Table 4. Summary of related and relevant studies on Moistube irrigation.

Author	Study title	Subject matter	Evidence[1]	Strength of Evidence	Location
Strength of Evidence: Strong (I)					
Bai et al. (2012)	The permeability and mechanical properties of cellulose acetate membranes blended with polyethylene glycol 600 for treatment of municipal sewage	Mechanical properties of semi-permeable membranes	+++	I	China
Bi et al. (2020)	Determination of the buried depth and pressure head under moistube irrigation based on principal component analysis	Moistube	+++	I	China
Corbatón-Báguena et al. (2016)	Comparison between artificial neural networks and Hermia's models to assess ultrafiltration performance	Semi-permeable membrane fouling	+++	I	Spain
Castejón et al. (2018)	Polypropylene-based porous membranes: influence of polymer composition, extrusion draw ratio and uniaxial Strain	Mechanical properties of semi-permeable membranes	+++	I	Spain
Dirwai et al. (2020)	Moistube irrigation (MTI) discharge under variable evaporative demand	Moistube	+++	I	South Africa
Dukes et al. (2005)	Soil moisture controlled subsurface drip irrigation on sandy soils.	Line source wetting geometry	+++	I	USA
Field (2010)	Fundamentals of fouling	Semi-permeable membrane fouling	+++	I	USA
Furuichi et al. (2008)	Evaluation of water quality using a plugging coefficient based on a pore blocking filtration model in the membrane filtration process	Semi-permeable membrane fouling	+++	I	Japan
Fan et al. (2020)	Establishment and validation of wetting pattern model of moistube irrigation in homogeneous soil	Moistube	+++	I	China
Fan et al. (2019)	Experimental study of pressure head on water migration in soil under moistube-irrigation	Moistube	+++	I	China
Gadkaree et al. (1994)	Methods of making semi-permeable polymer membranes	Mechanical properties of semi-permeable membranes	+++	I	USA
Guo et al. (2017)	An experimental study on the dynamic growth of onion with Moistube irrigation technology in green house.	Moistube	+++	I	China
Han et al. (2015)	Application test of micro-irrigation and fertilization integration technology in citrus orchard.	Fertigation using micro irrigation	+++	I	China
Isoda et al. (2007)	Effects of different irrigation methods on yield and water use efficiency of sugar beet [Beta vulgaris] in the arid area of China	Water conservation	+++	I	Japan
Jun et al. (2012)	Experimental study on characters of wetted soil in Moistube irrigation.	Moistube	+++	I	China
Kanda et al. (2021)	Coupling Hydrus 2D/3D and AquaCrop Models for Simulation of Water Use in Cowpea (*Vigna Unguiculata* (L.) Walp)	Moistube	+++	I	South Africa
Kanda et al. (2020b)	Modelling soil water distribution under Moistube irrigation for cowpea (VIGNA unguiculata (L.) Walp.) crop	Moistube	+++	I	South Africa
Kanda et al. (2020a)	Effect of Moistube and subsurface drip irrigation on cowpea (Vigna unguiculata *(L.)* Walp) production in South Africa	Moistube	+++	I	South Africa
Kanda et al. (2020c)	Soil water dynamics under Moistube irrigation.	Moistube	+++	I	South Africa
Kanda et al. (2019)	Moistube irrigation technology: A Review	Moistube	+++	I	South Africa

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Table 4 (*continued*)

Author	Study title	Subject matter	Evidence[1]	Strength of Evidence	Location
Kanda et al. (2020d)	Nutritional yield and nutritional water productivity of cowpea (Vigna unguiculata L. walp) under varying irrigation water regimes	Moistube	+++	I	South Africa
Kanda et al. (2018)	Hydraulic and clogging characteristics of Moistube irrigation as influenced by water quality.	Moistube	+++	I	South Africa
Kanda (2018)	Soil water dynamics and response of cowpea under Moistube irrigation.	Moistube	+++	I	South Africa
Khan et al. (2015)	Effect of porous pipe characteristics of soil wetting pattern in a negative pressure difference irrigation system	Porous pipes	+++	I	India
Li et al. (2019)	Increase of fertilizer solution concentration and biomass mixing proportion can enhance water and nutrients distribution in wetted soils under moistube irrigation	Moistube	+++	I	China
Liu et al. (2017)	Water-Salinity Distribution Characteristics in Wetted Soil of Moistube Irrigation under Different Pressure Heads and Soil Bulk Densities	Moistube	+++	I	China
Lyu et al. (2016)	Effect of Moistube depth and density on tomato yield and quality in solar greenhouse	Moistube	+++	I	China
Mataram et al. (2018)	Physical and mechanical properties of membrane poly-vinilidene fluoride with the addition of silver nitrate	Mechanical properties of semi-permeable membranes	+++	I	Indonesia
Niu et al. (2017)	Effects of Moistube depth and spacing on soil water and salt transports of tomato in solar greenhouse	Moistube	+++	I	China
Phuntso et al. (2011)	A novel low energy fertilizer driven forward osmosis desalination for direct fertigation: evaluating the performance of fertilizer draw solutions.	Semi-permeable membrane fouling	+++	I	Australia
Qui et al. (2015)	Experimental study on influence of water temperature on outflows of low pressure Moistube	Moistube	+++	I	China
Shen et al. (2020)	Effects of alternate moistube-irrigation on soil water infiltration	Moistube	+++	I	China
Sun et al. (2019b)	Effect of Moistube Fertigation on Infiltration and Distribution of Water-Fertilizer in Mixing Waste Biomass Soil	Moistube	+++	I	China
Sun et al. (2019a)	Effects of moistube patterns and fertilization levels on growth and physiological characteristics of blueberry	Moistube	+++	I	China
Sun et al. (2018)	Water use efficiency was improved at leaf and yield levels of tomato plants by continuous irrigation using semi-permeable membrane	Moistube	+++	I	China
Teeluck et al. (1998)	Discharge characteristics of a porous pipe micro-irrigation lateral	Porous pipe micro-irrigation	+++	I	Australia
Vela et al. (2009)	Analysis of membrane pore blocking models adapted to crossflow ultrafiltration in the ultrafiltration of PEG	Semi-permeable membrane fouling	+++	I	Spain
Xie et al. (2014)	Effects of silt content and particle size in irrigation water on Moistube outflow	Moistube	+++	I	China
Xue et al. (2013)	Effects of the tomato growth and water use efficiency in sunlight greenhouse by Moistube irrigation	Moistube	+++	I	China

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Table 4 (*continued*)

Author	Study title	Subject matter	Evidence[1]	Strength of Evidence	Location
Yu et al. (2017)	Effects of soil texture and water pressure on Moistube infiltration in vertical inserting mode.	Moistube	+++	I	China
Zhang et al. (2014)	Effects of soil initial water content on line-source infiltration characteristic in moisture irrigation.	Moistube	+++	I	China
Zhang et al. (2009)	Study on subsurface irrigation using ceramic pitcher on tomato cultivation in greenhouse	Ceramic pitcher	+++	I	China
Zhang et al. (2017)	Effect of Moistube-irrigation on crop yield and water use efficiency.	Moistube	+++	I	China
Zhang et al. (2017)	Characteristics of water and salt movement in soil under Moistube irrigation with brackish water.	Moistube	+++	I	China
Zhang et al. (2010)	Preparation and mechanical property of polymer-based biomaterials.	Mechanical properties of semi-permeable membranes	+++	I	China
Zhang et al. (2015)	Effect of tube depth of Moistube-Irrigation under plastic film mulching on soil water and salt transports of greenhouse tomato	Moistube	+++	I	China
Zhanga et al. (2019)	Effect of alternate irrigation on water and salt movement under Moistube irrigation	Moistube	+++	I	China
Zhu et al. (2018)	Effects of Moistube irrigation on growth and moisture-radiation use of coffea arabica under jujube shading cultivation.	Moistube	+++	I	China
Strength of Evidence: Moderate (II)					
Ashrafi et al. (2002)	Simulation of infiltration from porous clay pipe in subsurface irrigation	Porous clay pipe	++	II	Thailand
Cai et al. (2017)	Simulation of soil water movement under subsurface irrigation with porous ceramic emitter.	Porous ceramic emitters	++	II	China
Fan et al. (2018)	Simulation of Soil Wetting Pattern of Vertical Moistube-Irrigation	Moistube	++	II	China
Galindo et al. (2018)	Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semi-arid agro-systems.	Deficit irrigation	++	II	China
Guo et al. (2012)	A mini review on membrane fouling.	Semi-permeable membrane fouling	++	II	China
Hermia (1982)	Constant pressure blocking filtration laws-application to power-law non-Newtonian fluids.	Semi-permeable membrane fouling	++	II	
Petty et al. (1995)	Use of semi-permeable membrane devices (SPMDS) to determine bioavailable organochlorine pesticide residues in streams receiving irrigation drain water.	Mechanical properties of semi-permeable membranes	+++	II	USA
Siyal et al. (2009)	Measured and simulated soil wetting patterns under porous clay pipe sub-surface irrigation.	Porous clay pipe	++	II	Pakistan
Stucki et al. (2018)	Porous Polymer Membranes by Hard Templating–A Review	Mechanical properties of semi-permeable membranes	++	II	Switzerland
Zou et al. (2017)	Progress and prospects of Moistube irrigation technology research.	Moistube	++	II	China
Zhang et al. (2002)	Finite element modelling of soil water movement under subsurface irrigation with porous pipe and its application.	Porous pipe	++	II	China

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Table 4 (*continued*)

Author	Study title	Subject matter	Evidence[1]	Strength of Evidence	Location
Strength of Evidence: Low (III)					
Kang et al. (2017)	Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice	Water conservation	+	III	China
Yang et al. (2008)	Research prospect of the water-saving irrigation by semi-permeable film	Moistube	+	III	China

[1] Key: Substantiated (+++); partially substantiated (++); unsubstantiated (+) after Thomas, KM et al., (2019).

loam tested by Yu et al. (2017) were consistent with the Horton's empirical model shown in Eq. (1) (Horton, 1939, 1941; Beven, 2004):

$$f_p = f_c + (f_0 - f_c)e^{-kt} \tag{1}$$

where: f_p = infiltration capacity (LT^{-1}), f_c = minimum constant infiltration capacity (LT^{-1}) ,f_0 = infiltration-capacity at $t = 0$, ($L.T^{-1}$), k = decay coefficient, and t = time from beginning of infiltration event (T).

The study revealed that soil-water distribution was higher in red loam and sandy loam ($R^2 > 0.80$), whereas relatively low in sand ($R^2 < 0.70$). Jun et al. (2012) used a soil box to characterise wetted clay-loam soil under MTI and found out that Moistube produced a concentric wetting pattern and maintained soil moisture content of up to 90% of field capacity. In addition, MTI exhibited a high irrigation uniformity of 95.6%. Another study by Zhu et al. (2018) assessed soil wetting patterns under different heads of 1 m, 1.5 m, and 2 m for Coffea arabica under jujube shading. The results revealed a direct relationship between wetting geometry and head; the wetting zones increased with flow rate. Khan et al. (2015) and Fan et al. (2018) used a vertically placed Moistube to assess different wetting patterns on silty loam, sandy-loam, and loam soils at a pressure head of 1.5 m. The two MTI lateral configurations (horizontal and vertical) exhibited different soil-wetting geometries, with Khan et al. (2015) exhibiting a radial pattern which was a function of pipe diameter and pipe length. Kanda et al. (2020a) investigated the effect of soil texture and Moistube discharge on the soil water dynamics. They found that soil texture significantly affected the upward movement of water but horizontal and downward movement was not significantly different between sandy clay loam and loamy sand. It was also established that Moistube discharge significantly affected the soil water dynamics with a discharge of 0.2–0.4 $l.h^{-1}.m^{-1}$ being suitable for sandy clay loam and loamy sand.

Zhanga et al. (2019) investigated salt movement under alternate wetting and drying using MTI. The study incorporated saline water mineralised to degrees of 2 $g.L^{-1}$, 3 $g.L^{-1}$, 4 $g.L^{-1}$, and 6 $g.L^{-1}$. The study revealed that the degree of mineralisation influenced the infiltration rate. Furthermore, the study showed that the infiltration trend followed the Kostiakov empirical infiltration formula as in Eq. (2) (Kostiakov, 1932). The soil moisture and salt concentration were reported to be concentrated near the moistube.

$$f(t) = at^{-b} \tag{2}$$

where: where $f(t)$ = infiltration rate (LT^{-1}) as a function of time, a and b = equation's parameters and t = time (T).

According to Zhanga et al. (2019), the 3 $g.L^{-1}$ mineralisation level exhibited the highest infiltration rate. The general finding indicated that infiltration rate increased with the degree of mineralisation. Despite this, very few studies have investigated soil-water dynamics of MTI in heavy clay and coarse sand soil – the two extremes of soil texture.

Emitter spacing and depth are functions of soil hydraulic properties (Bar-Yosef, 1999) and crop root distribution. According to Kandelous and Šimůnek (2010) water flow in a homogeneous and isotropic soil is governed by Richard's equation. The equation can model 2D and 3D variably saturated flow (Deng and Wang, 2017). Schwartzman and Zur (1986) posited that the wetted geometry (depth and lateral geometries) exhibited by a point source emitter are dependent on soil hydraulic conductivity, emitter discharge and volume applied. Dabral et al. (2012) modelled the horizontal width (W) and vertical depth (Z) from a point source emitter as in Eqs. (3) and (4) (Dabral et al., 2012):

$$Z = t^{0.5}Q^{0.25}K^{0.25} \tag{3}$$

$$W = t^{0.67}Q^{0.5}K^{0.17} \tag{4}$$

where: Z = vertical wetted soil depth (L), W = horizontal soil wetted width (L), t = elapsed time (T), Q = discharge rate (L^3T^{-1}), and K = soil hydraulic conductivity (LT^{-1}).

Moistube exhibits a line source emission similar to subsurface drip emitters. A study by Singh et al. (2006) developed a conceptual empirical model that simulated wetting geometry from a line source subsurface drip line. The models are shown in Eqs. (5) and (6) respectively (Singh et al., 2006).

$$Z = A_1 V^{n_1}\left(\frac{K}{QD}\right)^{(n_1-0.5)} \tag{5}$$

$$W = A_2 V^{n_2}\left(\frac{K}{QD}\right)^{(n_2-0.5)} \tag{6}$$

where: A_i = constant of proportionality ($i = 1, 2$), D = placement depth (L), n_i = constant obtained graphically from the D and V relationship ($i = 1, 2$), and V = total amount of water in soil per unit length ($L^3.L^{-1}$).

An empirical model that simulates wetting patterns under MTI will inform irrigators on the optimal placement depths of MTI for various soils. As mentioned above, placement depth is a function of soil and crop type and it is worth noting that there is no "one placement depth fits all scenario". Kanda et al. (2020) summarised the optimal lateral spacing for various crops under soils (Table 5).

It can be hypothesised that the MTI wetting geometry is also a function of placement depth (D), soil hydraulic conductivity (K), total amount of water in soil per unit length (V), discharge per unit length of lateral (Q), and the matric potential per unit mass of soil (ψ). The relationship can be modelled according to Eq. (7).

$$Z, W = f(D, K, V, Q, \psi) \tag{7}$$

Developing and validating an empirical model that will simulate the wetting geometries based on the above parameters will significantly open new research frontiers around the MTI line source emitter.

3.2.3. Waste-water use and membrane fouling

A total of 9 out of 44 (n = 9, 20%) studies related to semi-permeable membrane fouling. Membrane fouling is a process whereby fine particles are deposited onto the surface of the membrane, leading to membrane performance degradation (Furuichi et al., 2008). To counter the

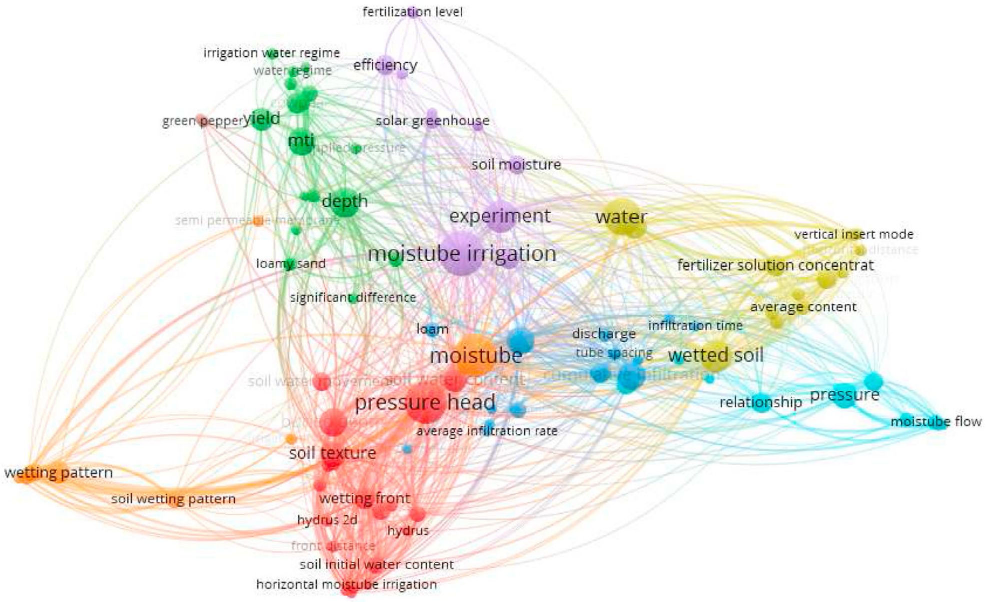


Figure 2. MTI literature network visualization (VOSviewer).

increased competition for freshwater resources, treated waste-water from domestic, industrial and agricultural sources have been adopted as an alternative source for irrigation water.

Arid regions in China and Mexico have adopted treated sewage water for irrigation (Friedel et al., 2000; Puig-Bargués et al., 2005; Liu and Huang, 2009). Also, waste-water has been reported to be a significant driver of emitter clogging. For example, Puig-Bargués et al. (2005) investigated the effects of varying effluent treatment on irrigation uniformity of drip irrigation kits. The study revealed that secondary effluent treatment caused clogging as compared to tertiary treatment. No previous research has investigated the effects of different effluents on the clogging of Moistube nano-pores. A study by Liu and Huang (2009) revealed that drip emitters subjected to laminar flow were susceptible to clogging compared to emitters having turbulent flow. Parameters such as coefficient of variation (CV), emission uniformity (EU), Christiansen uniformity coefficient (CU) are used to evaluate and assess emitter performance (Liu and Huang, 2009). Semi-permeable membranes such as Moistube are sensitive to fine aggregates, for instance Xie et al. (2014) revealed that particle size in the range 37 μm–74 μm clog the nanopores. In another study, it was established that suspended and dissolved solids caused clogging of Moistube laterals where the former caused severe clogging than the latter(Kanda et al., 2018).

Microbiological fouling is accelerated by the presence of microorganism such as vegetative matter, algae, and bacteria. The latter (bacteria) attaches to the polymeric membrane via bio-adsorption, bio-adhesion, and multiplication (Guo et al., 2012). Researchers need to investigate the suitability and efficiency of MTI using waste-water and how various plugging stages form throughout an irrigation cycle.

Hermia (1982) in his filtration model clarification characterised cross-flow and dead-end filtration membrane models as in Eq. (8) (Hermia, 1982). The fouling was typified as complete blocking, intermediate blocking, standard blocking, and cake layer formation (Hermia, 1982; Furuichi et al., 2008; Vela et al., 2009). Understanding semi-membrane (SPM) fouling or plugging mechanisms facilitate more in-depth knowledge on the capacity and efficiency of the SPM under differential operating conditions such as pressure, flow velocity, and temperature to mention a few (Corbatón-Báguena et al., 2016).

$$\frac{d^2t}{dV^2} = \left(\frac{dt}{dV}\right)^n = \alpha\left(\frac{1}{J}\right)^n \tag{8}$$

where: t = filtration time (T), V = filtrate volume per unit area ($L^3.L^{-2}$), J = filtration velocity (flux) (LT^{-1}), α = plugging coefficient and, and n = constant of proportionality for constant pressure filtration of a Newtonian fluid.

The n value ranges from 0 to 2, with complete blocking ($n = 2$), intermediate blocking ($n = 1$), standard blocking ($n = 3/2$), and cake layer ($n = 0$) (Vela et al., 2009) (Figure 4). The model can be adapted to determine the fouling or plugging coefficient of MTI using different waste-water effluent. The higher the plugging coefficient, the rapid the clogging of the membrane.

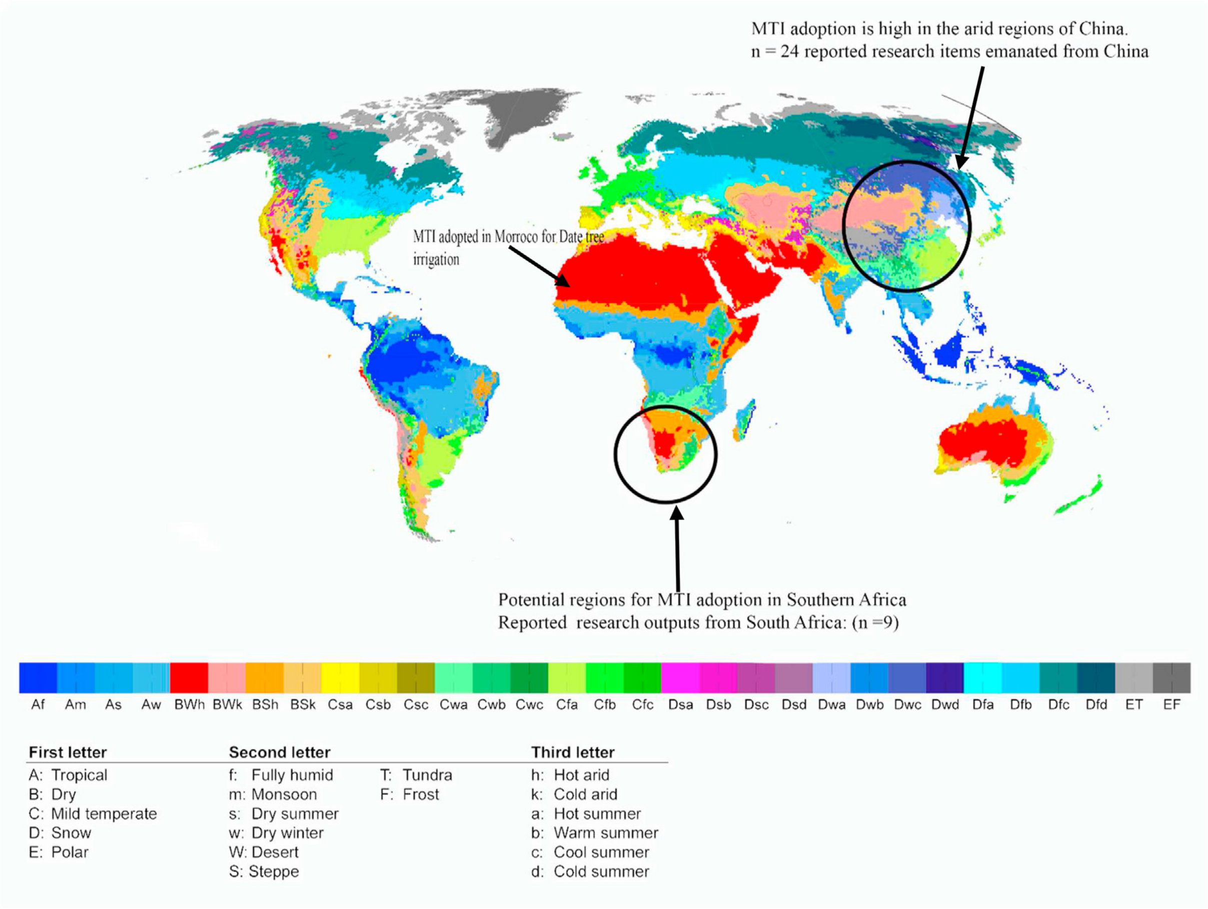
3.2.4. Fertigation in moistube irrigation (MTI)

The application of fertilizer solution together with irrigation water under micro-irrigation techniques is an efficient method which ensures that the nutrients are supplied to the root zone of the crop. The search query and screening process retained 2 articles on fertigation (n= 3, 0.06%), presenting a potential research gap into fertigation under MTI.

Fertigation has been practised under SDI for a long time. In a fertigation experiment under Moistube irrigation, Li et al. (2019) established that nitrate-nitrogen distribution was more uniform while the available phosphorus and potassium were accumulated within the 10 cm radius from the Moistube. The movement of nutrients in the soil follows the soil wetting pattern which is influenced by the parameters described in the preceding sub-section. In a study to determine the soil water and salinity

Table 5. Summarised MTI placement depths for various crop under different soil types (Source: Kanda et al., 2020).

Crop	Soil type	Placement depth (cm)
Tomato	Clay loam	10 and 15
Tomato	Sandy loam	20
Maize	Clay loam	20
Wheat	Clay loam	20
Cowpea	Loam	15
Cabbage	Loam	3.5
Onion	Loam	4
Sunflower	Clay loam	20
Green pepper	Clay loam	20
Water spinach	Loam	15



MTI adoption is high in the arid regions of China.
n = 24 reported research items emanated from China

MTI adopted in Morroco for Date tree irrigation

Potential regions for MTI adoption in Southern Africa
Reported research outputs from South Africa: (n =9)

Figure 3. Climates in Africa according to classification Köppen Geiger climate, adapted from Kottek et al. (2006).

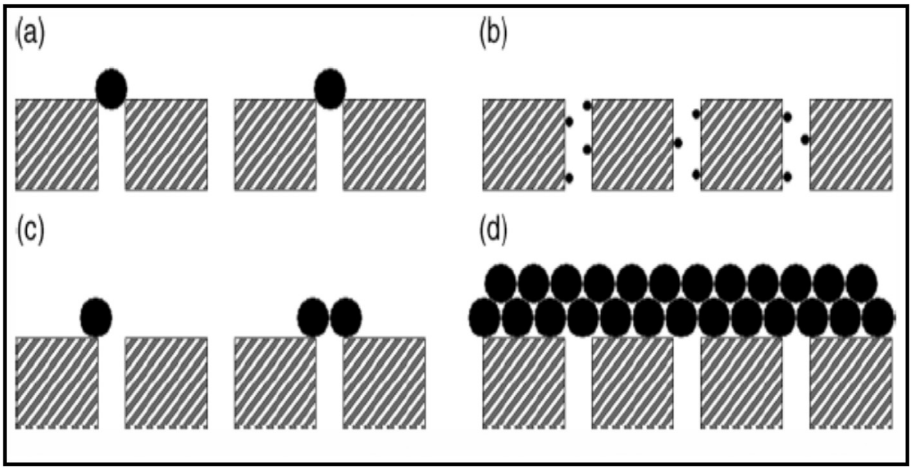


Figure 4. The various types of membrane fouling (a) complete pore blocking, (b) internal pore blocking, (c) partial pore blocking, and (d) cake formation (after Field, 2010).

movement under MTI (Liu et al., 2017), found that bulk density and system pressure influenced the movement of soil moisture, nitrates and potassium. In this study, three pressure heads (1, 1.5 and 2 m) and three bulk densities of 1.00, 1.15 and 1.30 g.cm^{-3} were used. The area of fertigation requires further research especially in terms of the optimum pressure heads and fertilizer concentrations bearing in mind the clogging characteristics of Moistube. Understanding solute movement for different textured soils under MTI is aids in effective optimal fertiliser application.

4. Conclusions

The study concluded that in agricultural regions were MTI has been adopted there has been boosted yields and improved WUE and WP. MTI can potentially be adopted in sub-Sahara Africa for improved irrigation water use efficiency (fWUE) and Water Productivity (WP). Adoption and documentation have been predominant in the arid regions of China and partly South Africa, hence a bulk of literature has been limited to Chinese, thus creating a literature gap for proper documentation. The study also concluded that there exist research gaps around the subject area. Minimal empirical investigations on MTI subject matter limits the availability of literature into the body of knowledge. The research gaps are summarised below.

Clogging presents a challenge literature has analysed the clogging of the nanopores due to total dissolved and suspended solids (TDS and TSS). Evidence of how Moistube discharge characteristics are affected by waste-water effluent is limited. This area requires further research considering the importance of waste-water re-use in reducing the pressure on freshwater resources. The aspect of clogging under MTI can be assessed together with fertigation, which has been demonstrated to improve yields and plant biomass.

Soil texture influence soil water and solute dynamics. Soil water and solute dynamics under MTI have not been thoroughly analysed, with the conclusions based on SDI. The soil water dynamics are hypothesised to be symmetrical and asymmetrical in heavy clay and coarse sand soils, respectively. Empirical investigations are required to ascertain the phenomenon. There is limited evidence on how MTI influences solute movement in the vadose zone. This also limits fertigation application in MTI.

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