

Low-pressure subsurface porous diffuser irrigation system for kitchen wastewater reuse in urban vegetable cultivation: A review of hydraulics, clogging, and automation

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ABSTRACT

By 2050, up to 2.4 billion people are expected to be affected by urban water scarcity, which has led to an interest in the reuse of kitchen wastewater as a low-cost irrigation resource. Previous research has shown that clay pot irrigation is a traditional water-use-efficient irrigation method that can be used with moderately saline water and is several times more efficient than conventional irrigation. This review aims to compile the latest literature on the hydraulics, clogging, and Internet of Things (IoT) based automation of such systems for urban vegetable production using kitchen wastewater. Seepage rates have been previously determined under clean water conditions, and simple pretreatment has been found to significantly reduce organic and solid loads. But previous clogging tests, which were mostly conducted with saline, sediment-laden or synthetic wastewater, not with real kitchen wastewater, have shown that hydraulic degradation is very severe under poor water quality, which is why pretreatment is necessary. Earlier research on IoT integration shows that low-cost reference pot level sensing loops can be used to automate refilling, but they are not able to detect individual emitter clogging. Favorable yield and water productivity gains have been reported in prior agronomic and economic studies, but not under actual kitchen wastewater. Together, these results suggest technical feasibility and highlight key areas of long-term hydraulic, agronomic, and economic validation that require integrated field testing prior to household-scale adoption.

Keywords: ceramic emitter, clay pot irrigation, household wastewater, IoT irrigation, kitchen wastewater, subsurface porous diffuser, smart irrigation.

INTRODUCTION

With an increasing population and continuing climatic changes, the difference between demand and supply of water becomes larger. According to a worldwide study, 933 million people in urban areas were already experiencing water shortages in 2016, while the number of water-lacking city inhabitants could be between 1.7 and 2.4 billion people by 2050. The same research reveals that the two countries with the largest number of water-lacking urban population are India (222 million people) and China (159 million people) as of 2016, while the number of water-short cities could increase from 193 at present to 284 in

a few decades to come, including an increasing number of megacities (He et al., 2021). In light of statistics like these, policymakers and scholars are increasingly looking to move away from traditional approaches such as constructing additional reservoirs or exploiting greater amounts of underground water and turning to more novel approaches that start at home.

This approach involves household wastewater reuse, whereby, rather than allowing used water to simply flow down the drain and be flushed into sewer systems, people can collect the water for reuse on a second occasion, mostly for irrigation purposes. The reason why greywater, namely wastewater that is relatively mild and originates

from kitchens, showers, laundries, and hand basins, and does not include any human excreta, and does not carry high amounts of pathogenic substances and nitrogen, has recently been attracting considerable attention as an alternative source for reuse and recycling is the aforementioned reasons. The proportion of greywater in overall household consumption is considerable; thus, reusing it may significantly reduce the need of a household for fresh municipal water supply (Khajvand et al., 2022). Yet, kitchen wastewater is viewed more as a hassle that must be flushed out rather than a resource, despite the fact that greywater may come with nutrients like nitrogen and phosphorus that are necessary for plant growth in addition to pollutant load that can be removed easily compared to that of municipal sewage (Hamidi, 2025). However, it must be noted that there are some problems with kitchen wastewater. It always consists of small portions of organic materials such as food particles, oils and grease, detergents, and suspended solids that accumulate if wastewater is not treated properly before it enters the soil or an irrigation system. The key problem of “useful and dirty” is exactly what the review is trying to address. The task was to direct regular household kitchen wastewater into the vegetable garden in an easy and safe manner without using costly treatment facilities and blocking the irrigation system.

The technique that already comes close to meeting this description, refined over centuries rather than invented from scratch, is the low-pressure subsurface porous diffuser irrigation system (LPSPDIS)/clay pot irrigation/pitcher irrigation/olla irrigation – an old technique with a new twist. In this technique, the porous container is filled with water and buried next to the root zone of the plant. Through capillary action and moisture gradients in the soil, water seeps through the pores of the earthen vessel to reach the soil. As the rate of seepage reduces due to soil moisture and increases when plants take water from the soil, the irrigation system is regarded as “self-regulating,” as the water flows in accordance with the needs of the plant (Bainbridge, 2001). Similarly, comparative evidence showed that clay pot irrigation can be very efficient in water use with good crop productivity. For cabbage and tomato, water-use efficiency was about 42% and 47% greater than with drip irrigation, respectively. Generally, the use of clay pot irrigation is very promising for water-efficient crop production with satisfactory yield. Comparisons should be made with caution, as data were

obtained from various studies and experimental conditions (Nalwade et al., 2026). Whereas a buried clay pot would self-regulate to an extent, it still requires one to refill it manually and some degree of guesswork as far as determining the amount of water that is required by the plants on any particular day. Here, the Internet of Things (IoT) comes into the picture, for low-cost soil moisture sensors, small microcontrollers, and wireless communication modules can be used for monitoring the moisture levels of the soil and then initiate irrigation as soon as certain soil moisture levels have been achieved (Pramanik et al., 2022).

However, according to the latest systematic review of the use of IoT sensing for irrigation management, which included research conducted from 2014 to 2024, remote monitoring and control of irrigation systems is the most frequent application of IoT sensing, while optimization of water use and monitoring of soil moisture and weather are among the most common secondary applications (Abdelmoneim et al., 2025). This is confirmed by the results of several recent field tests, which showed that an IoT-powered drip system used for irrigation of crops (sweet corn) from 2020 to 2022 irrigated only when soil moisture was below a particular threshold, stopping at field capacity. In comparison with the evapotranspiration schedule, IoT system used less water and increased yield (Vinod Kumar et al., 2025). Therefore, by aiming to use kitchen wastewater for household vegetable cultivation, the main objectives are decided as follows:

- to outline what is known about the hydrodynamics of a low-pressure porous diffuser,
- to address the problem of clogging of the diffuser caused by the use of kitchen wastewater,
- to evaluate the actual feasibility of the implementation of LPSPDIS in relation to the simple and low-cost arrangement,
- to determine the gaps in the current state of the research that prevent making this idea applicable and safe.

MATERIAL AND METHODS

Wastewater source to crop uptake

It is most appropriate to consider this particular system as a single process flow, rather than a series of independent components. Kitchen sewage arising from domestic kitchens on an everyday basis

from vegetable washing, dishwashing, and cleaning of eating utensils, goes through preliminary treatment involving screening, grease trapping, and short-time retention, which prevents food bits, grease, and oils from entering the system and causing harm to the subsequent parts of the system. This partially treated kitchen sewage is channeled into underground clay pots or ceramics, through which the sewage infiltrates into the soil at low-pressure seepage, rather than forced pressure, spreading out and downward into the root zone of the soil. Then, the crop takes advantage of this water content and any nutrients dissolved within through the roots. On top of this physical process, there is another automated feedback loop centered around the reference pot. Rather than individual sensors for each plant, the reference pot is configured in such a way that the water content of this pot will always be equal to that of any pot in the system, and it contains two level probes at the top and at the bottom of the pot. When the level of water content drops to the bottom level probe, the controller activates a pump which fills all the pots with screened water. When the level rises up to the upper level probe, the controller turns the pump off, completing the loop without having to measure soil moisture content individually. This entire path is illustrated in Figures 1 and 2.

Starting at the top and moving downwards, the left column indicates the core pathway of water when reading the figure from top to bottom,

the left-hand column depicts the main flow of water as a linear process with five sequential steps, production of kitchen wastewater at source, pre-treatment of this wastewater, treatment of this wastewater in buried, percolation of water in soil root zone, and uptake of the treated water by the crops. On the right hand side of the diagram is the reference automation process which is parallel to the above water flow process rather than an alternative to it, the reference is depicted level with the step and connected to it by a “shares water level” bidirectional arrow because the reference always mimics the level of the pots, bottom and top probes of the reference are one row below the step and supply a “level signal” to the controller; while the decision from the controller is supplied to the step by a “triggers fill pump” arrow which is situated in storage tank. It is intentionally depicted as two parallel lines and not just one straight line because it clearly shows that the automation system watches and recharges the system without interfering in any way in the six steps of the physical process that the water goes through, and that it functions based only on the level of water in the reference.

Key interlinked processes

There are four processes responsible for the performance of this system, and none of these processes can be explained without considering

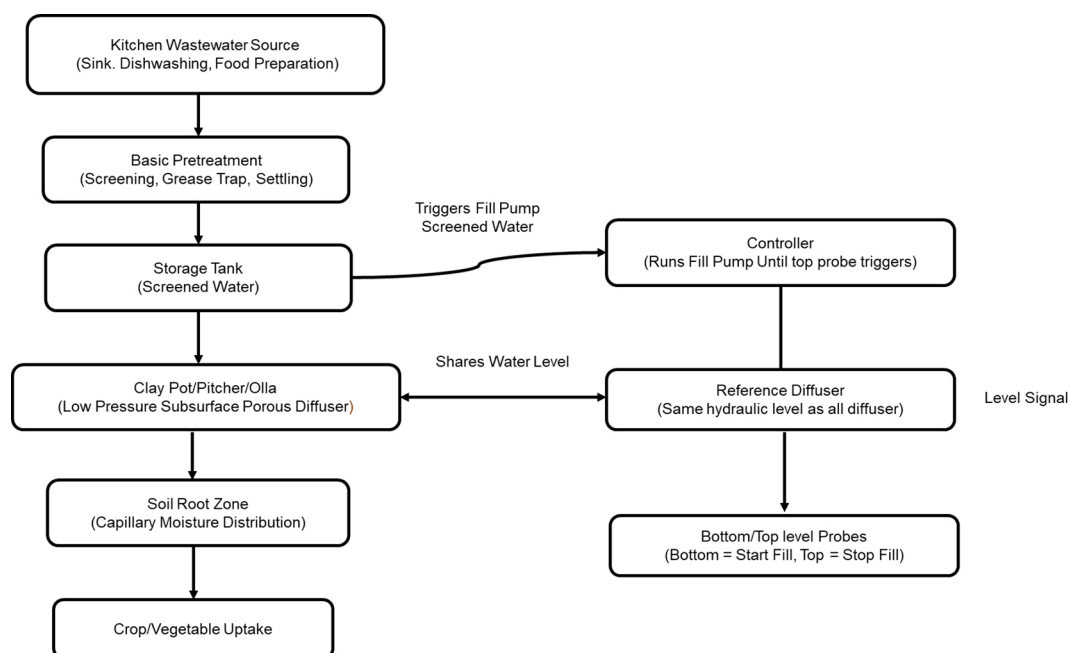


Figure 1. Integrated process flow of LPSPDIS for kitchen wastewater

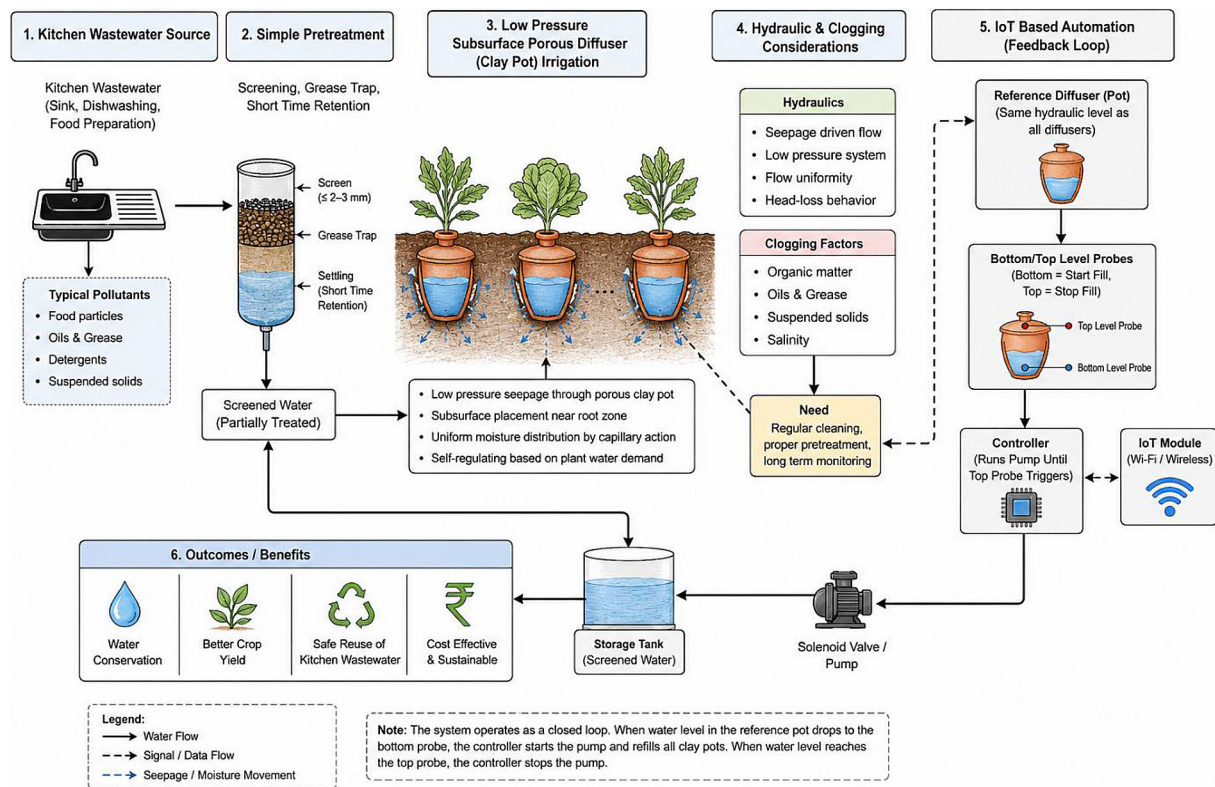


Figure 2. Conceptual framework of the integrated low-pressure subsurface porous diffuser irrigation system for kitchen wastewater reuse, incorporating pretreatment, clogging considerations, and IoT-based automation

the other three processes. The hydraulics process forms the starting point, the thickness of the wall, the pore network, and the composition of the raw material, combined with the hydrostatic pressure of the water over the determine the rate at which water infiltrates into the soil in clean water (Bainbridge, 2001; Vaghei et al., 2023). The next step is bio-clogging: since kitchen wastewater contains suspended particles, fats, and organics that clean irrigation water does not contain, the particulate and biofilm content gradually accumulates inside the pores of the wall. Such an evolving pattern of seepage behavior is precisely what the plant soil response will have to cope with as the frequency and the way of water application evolve. As a result, there will be an evolving pattern of soil moisture and nutrient availability to the plants based on kitchen wastewater being rich in nutrients (Hamidi, 2025; Khajvand et al., 2022). The automation technology brings all four parts into the chain; however, such a process is realized indirectly due to the fact that the system is sensing only one reference pot for the level of water instead of the soil moisture content at each plant individually (Abdelmoneim et al., 2025; Vinod Kumar et al., 2025). This is a clear-cut simplicity compromise that should be mentioned explicitly.

While a reference pot is much less expensive and easier to maintain than a sensor for each plant, it relies on the premise that all the pots drain at approximately the same rate, a premise that will be increasingly difficult to satisfy as a result of bio-clogging, which never develops uniformly in all pots of a network. Figure 2 illustrates this dependence in the form of a closed causal loop and not four separate variables, and the main thesis that this review is based on is the interdependency of these four phenomena.

Figure 3 presents the processes in a circular form instead of a linear form. The names of each arrow describe the mechanism through which an effect moves from one process to another. In terms of hydraulics, “reduces effective flow” refers to the fact that clean water hydraulic capability is just the beginning, because the accumulation of particulates and biofilm will reduce it. “Alter’s delivery to roots the arrow coming from bio-clogging towards plant soil response, indicates that such reduction does not remain inside, it impacts the delivery of water and nutrients directly to the plants. Lastly, reference pot drains faster, trips low probe from plant soil response to automation indicates that the system does not measure either the clogging or the state of water in the plant; it only

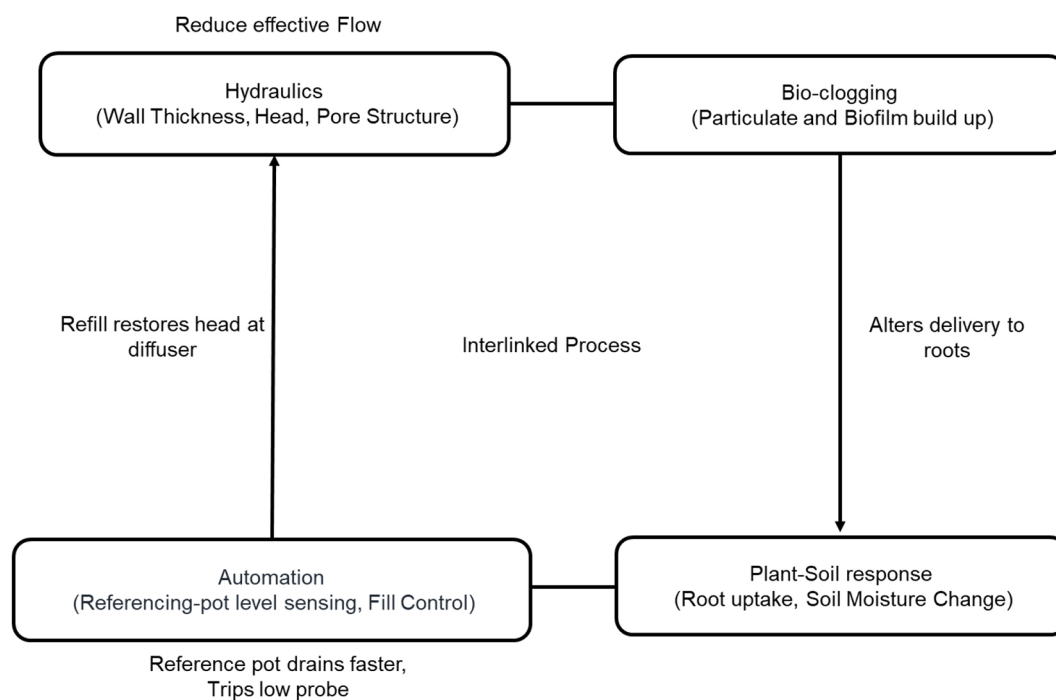


Figure 3. Key interlinked processes governing system performance

measures the combination of both via drainage of the reference pot. In addition, the arrow connecting the refill restores head at process from automation to hydraulics demonstrates how the control of the system will lead to the resetting of the hydraulic head throughout the entire system, not the repair of biological blockage at the root cause or the particular pot that has been most affected by clogging. The layout of the four processes is intended to make the singular statement that the four boxes are all dynamic and cannot be thought of as a static trait because each one affects what the subsequent box in the loop has to deal with, especially the reference pot configuration.

Sources, composition, and variability of kitchen wastewater

Dish washing, washing vegetables, cleaning utensils, cookware, and cooking equipment are the primary sources of kitchen wastewater, which is a significant portion of household greywater. The amount of greywater produced can differ significantly depending on the home's size, structure, water consumption habits, socioeconomic status, and food habits. In a previous study and as shown in Figure 5, it was reported that the average domestic greywater generation per capita per day was 62 L in a year-long study of an Indian household, where the kitchen wastewater was the highest at 37%,

followed by the bathroom wastewater at 31%, laundry at 21% and hand basin at 11% (Shaikh and Ahammed, 2022). There was also a significant variation in domestic water use patterns, with another Indian study reporting a significantly larger domestic greywater generation of 108 lit./capita/day (Delhiraja and Philip, 2020). The details are illustrated in Figure 6. The variations highlight that estimates of the amount of wastewater generated from individual houses or a small number of houses should not be interpreted as representative of the population as a whole without considering local socioeconomic and behavioral conditions. A comparative analysis of countries with high and low per capita income also showed that household water use behavior was more correlated with greywater generation than climate alone (Mohan et al., 2024). Previous study reported that the total household water consumption, kitchen and dish-washing activities are estimated to use about 17% of the water, whereas bathing and showering uses 32%, and toilet flushing 26%, illustrated in Figure 4 (Manna, 2018). These findings highlight the substantial contribution of kitchen-related activities to household water use and greywater generation, supporting their consideration as a potential source for household-scale water reuse.

The composition of kitchen wastewater is typically not as heavily contaminated as toilet wastewater, but can have significant variation

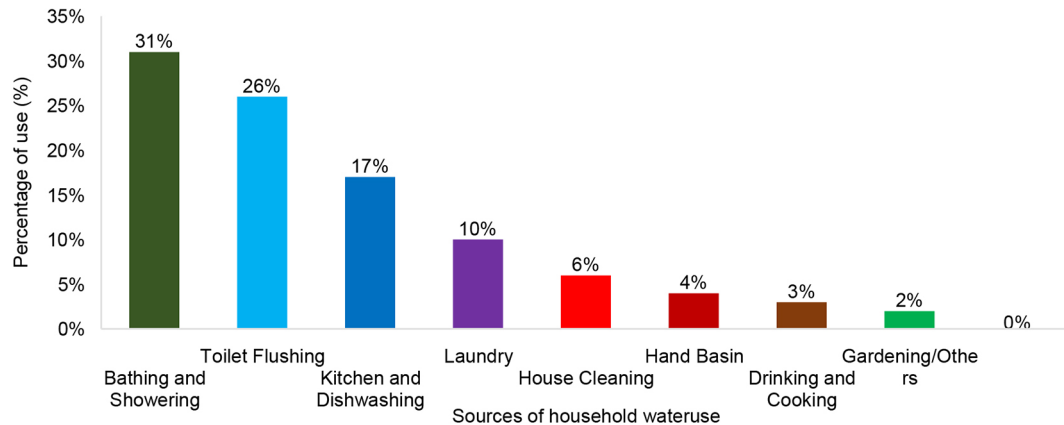


Figure 4. Distribution of household water use by domestic activity (Manna, 2018)

in levels of food residue, detergents, suspended solids, and fats, oils, and grease (FOG) resulting from household activities. Therefore, application directly to the soil is not recommended without appropriate pretreatment. Screening and filtration to discard coarse solids and FOG can enhance the feasibility for local irrigation use, and kitchen wastewater can be considered as a potentially viable additional source of water for household vegetable cultivation, especially in water-limited urban and peri-urban settings.

Physicochemical and organic load characteristics

Kitchen wastewater has been consistently observed to be the most organically loaded stream among the greywater streams. Earlier studies in Indian household kitchen wastewater represented about 60% of the total organic load carried by greywater, quantified in terms of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), even though it was only 37% of the volume

of greywater (Shaikh and Ahammed, 2022). Comparison from other studies conducted in various countries revealed total suspended solids (TSS) in kitchen wastewater as 134 mg.L^{-1} to 1300 mg.L^{-1} , BOD of 100 mg.L^{-1} to 1850 mg.L^{-1} and total nitrogen in kitchen wastewater of around 1.5 mg.L^{-1} to 48 mg.L^{-1} along with relatively low slightly acidic pH of 5.6 to 8 (Mohan et al., 2024). FOG is also much more difficult to define consistently, partly due to the fact that the majority of the more detailed FOG statistics available in the literature pertain to commercial food service kitchens, not to individual households (Shamika et al., 2024). It is crucial to highlight this specific scale difference; while a home kitchen produces less FOG per day than a restaurant does, the vast majority of available FOG concentration data pertain precisely to the commercial kitchen literature, hence making this review, like any other on the subject, extrapolate instead of citing an exact household FOG statistic. As a whole, excepting wastewater from toilets, greywater constitutes approximately 50% to 80% of household wastewater worldwide

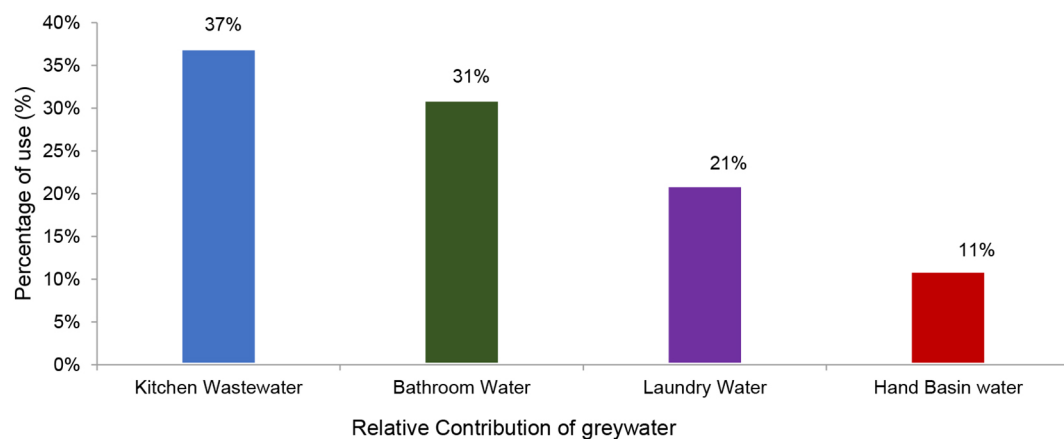


Figure 5. Distribution of household greywater generation by source

(Filali et al., 2022). Kitchen wastewater may be considered a part of greywater, which has high organic loads and suspended solids, but not an independent category of effluents. In comparison with laundry water, kitchen wastewater has higher organic loads and suspended solids, but laundry water has higher loads of surfactants, heavy metals, and phosphate loads due to detergents (Delhiraja and Philip, 2020; Shaikh and Ahammed, 2022). Water from bathrooms and hand basins has the highest pathogen load compared to organic matter because they easily get mixed with the residues of personal care products (Shaikh and Ahammed, 2022). The cross-stream comparison also brings to light a research methodological issue that needs to be mentioned explicitly.

Pretreatment requirements

It is difficult to consider an option where the wastewater is directly discharged into a buried clay pot system since food particles and FOG will result in clogging, while the composition of the wastewater is way beyond the acceptable limit of organic load in terms of direct soil application. The treatment process used in all the low-cost household wastewater treatment literature has three stages, which are coarse screening to eliminate food particles, a grease trap or something similar to prevent FOG from clogging the pipes, and finally a simple filter, usually composed of sand and gravel and sometimes even charcoal, as illustrated in Figure 6.

The sequence, screening, grease trap, and multi-layer filtration, recurs across the literature discussed in this section, ending at the point where

pretreated water would enter the clay pot. There is quantitative proof that this kind of relatively cheap process works in households, as demonstrated in a pilot-scale study in India, where the efficiency of COD removal using a multiple-layer filtration system designed for household greywater was found to be 85.98%, the efficiency of BOD removal was 86.28%, and the efficiency of TSS removal was 94.44% (Patil et al., 2022). Literature reviews indicate that there is more evidence that supports this point; physical treatment of kitchen sink greywater was shown to result in a decrease of BOD and COD levels by around 80% (Filali et al., 2022). This information stems from one single pilot-scale experiment and not a synthesis of several systems, so it should be viewed as a demonstration of what is possible to achieve with simple filtration and not a performance expectation for all household arrangements. Nevertheless, the crucial point that lies between all the evidence mentioned above is the following: none of the pretreatment studies described above was verified using a low-pressure gravity-fed clay pot as the downstream irrigation equipment. The efficiency values provided by (Patil et al., 2022) and others were determined on the basis of the general criteria for water reuse and storage tank effluent discharge, not on the basis of the specific values for clogging of a porous emitter operated with a very low working head

Clay composition, hydraulic behavior, firing temperature, and pore structure

The whole purpose of a porous clay is based on a contradiction: its walls must be solid enough

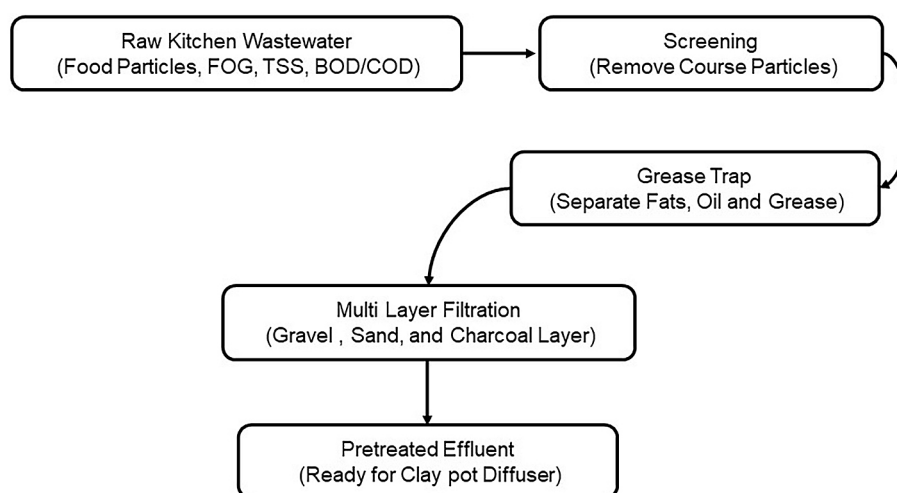


Figure 6. A low-cost pretreatment train for household kitchen wastewater

to maintain a shape and to resist burial, but porous enough to allow water to pass through continuously. Most of this balance is determined during manufacture, through the ratio of clay to sand or other filler, and the temperature at which it is fired. The effect of firing temperature on the porosity of ceramics has been well documented, especially in the field of brick and pottery production, with a decrease in porosity as firing temperature increases, while mechanical strength increases, for decades (Vaghei et al., 2023). Most of the recent research on clay based irrigation does not attempt to address this trade off directly, but instead, it varies the amount of rice husk and rice bran incorporated into the raw clay before the firing process, with a significant, mostly linear relationship between the added organic matter and the discharge measured under hydrostatic pressures ranging from 10 kPa to 100 kPa (Vaghei et al., 2023). On its own, there are now some commercial and experimental porous emitters that are made with a purposefully graded porosity, including pottery, which has three different porosities, 10%, 21%, and 31%, specifically for different salinity and pressure conditions (Mahler, 2024). There is real “evidence” below this that is very little of the recent, irrigation-specific literature actually reports firing temperature as an experimental variable in its own right. The knowledge acquired on the effect of the firing temperature on the pore structure is mostly transferred by analogy from the literature of ceramics and the construction materials industry, as well as from brick making and filter studies, not from measurements performed under field conditions on irrigation emitters. This is important because the mineralogy of the clay has a significant influence on the sintering behavior, and a firing regime that is optimal for a brick’s compression strength may not be a regime that yields the pore size distribution irrigation requires. This is one of the least studied design parameters in the entire system, despite being perhaps the most significant for all the other factors mentioned in the remainder of this section, and there are no studies that directly modify the irrigation grade clay body and report seepage results. The seepage rate of buried clay is controlled by the same fundamental physics that control flow through any porous medium; it is proportional to the saturated hydraulic conductivity (K_s) of the wall material, and to the hydraulic head of water against which it is pushing, but also depends on wall thickness and total wetted surface area. In

another field study continuous operation was conducted for two years, and the authors of the above two studies concluded that the working range of the ceramic emitters under low pressure condition is broad and should be considered as 20 cm to 50 cm head with a hydraulic conductivity of 0.1 cm.h^{-1} to 1.9 cm.h^{-1} (Cai et al., 2021; C. Yao et al., 2021). The pressure discharge response of the capsules made of modified clay with organic matter, as mentioned above, also demonstrated a near-linear increase in discharge with increasing hydrostatic pressure, up to 100 kPa, indicating that pressure discharge behavior in this modified system remains proportional to Darcy’s law despite the modification of porosity with additives rather than firing.

Sizing, wetting front dynamics, and soil moisture distribution

Pressure head and hydraulic conductivity of the emitter have been reported to have a significant effect on the discharge rate, especially in loamy soils (Mahler, 2024). This is a narrow evidence base as the vast majority of the studies on the wetting front of clay based emitters have been conducted on a single soil texture, normally loam or sandy loam, and burial depth has been shown to only have a small direct effect on discharge itself but a significant effect on the time taken for the wetting front to reach the soil surface and lower boundary of the root zone (Malchev et al., 2025). In the same study, emitter operation with a higher pressure head and shallower depth of burial has been correlated to lower irrigation water application efficiencies. Critically, the wetting front literature used in this review does not focus on the extreme endpoints that are the very heavy clay soils and the very highly sandy soils; this is directly relevant for this review’s proposed system, a kitchen garden, which could reasonably be located anywhere on that texture range. The size and depth of the diffuser are not independent variables, but are directly related to the hydraulic and wetting front behavior discussed above. A large water reservoir and a greater wetted surface will increase the water holding capacity and lengthen the time between watering, but a large pot will also require more excavation and a larger space around the pot to allow unobstructed root growth, which may be difficult if you are in a dense kitchen garden. The disadvantage of shallow burial is that the wetting front is nearer to the

soil surface, where the seedling roots and shallow rooting vegetable roots reside, the disadvantage of deeper burial is that evaporative loss from the soil surface will be less but there is a risk of water being below the active root zone of shallow rooted crops, particularly early in the crop's growth when roots are shallow. An increase in operating pressure and shallow burial has been associated with a loss in application efficiency; therefore, the diffuser size cannot be optimized independently of the depth of burial and the hydraulic head (Malchev et al., 2025). In the case of a system designed around a shared reference diffuser, there is an additional, often unnoticed implication that the water level of the reference diffuser can only be a valid indicator of the water level for any other buried pot in the system if the diffusers have reasonably similar wall properties.

Comparison with other irrigation methods

Throughout the various crops evaluated, clay pot and ceramic emitter irrigation systems have proven to be more water-efficient than conventional irrigation systems. In earlier studies for the cultivation of melon, the yields were similar (25 t.ha^{-1} and 33 t.ha^{-1}), and about 13 times less water was used than for flood irrigation. From 2021 to 2023, the irrigation water productivity of more advanced systems, like subsurface ceramic emitters in sweet cherry orchards, exceeded that of standard drip irrigation by more than 12 times (Malchev et al., 2025). In addition to these results, subsurface drip irrigation also achieved significant improvements over surface drip irrigation, increasing overall yield by 5.39% and water productivity by 3.97% (Liu et al., 2024). In total, these findings highlight the ability of these low-flow irrigation technologies, especially clay/ceramic emitters, to significantly improve water use efficiency without sacrificing or degrading crop yields. The potential advantages of the two clay pot rows, and the Self-Regulating Low Energy Clay Based Irrigation (S.L.E.C.I.) row, are enormous when compared to the large drip versus drip meta-analysis, which reports single-digit percentage gains for essentially the same underlying idea delivering water closer to the root with less exposed surface area. The type of irrigation being compared, the clay pot studies are primarily comparing to flood or hand irrigation, which are generally inefficient methods, whereas the subsurface drip irrigation (SSDI) meta-analysis compares to

surface drip, which is already a relatively efficient method. Perhaps the only clear gap in the review is the absence of a head to head comparison of clay diffuser versus a drip, for a similar crop, under similar pressures and soil conditions.

Clogging mechanisms: Physical, organic (FOG), and biofilm-related

There are no direct bio-clogging studies on clay pot irrigation found during the studies, so a similar concept used in the ceramic emitters is illustrated to understand the bio-clogging effect and remediation. Three separate mechanisms are typically grouped together under the umbrella of the word “clogging”, which are important for the diagnostic and treatment of each. It can be directly visualized via X-ray computed tomography (CT) imaging, which revealed that the clogging material was not homogeneously covering the internal geometry of the emitter but instead was unevenly distributed throughout the pore structure or flow channel (Y. Yao et al., 2025). The difference in clogging is of the type, a living layer of microorganisms and their extracellular excretions, which grows on the walls of the pores, after the source of water has been filtered. Clogging occurs due to the growth of Acute Otitis Media (AOM) on the inner surfaces of microporous ceramic emitters, and this growth process can be measured over time, and it measurably decreases the pore diameter of the emitters (Du et al., 2024). Indeed, the closest evidence to the mechanism most directly relevant to kitchen wastewater, namely organic and FOG-related clogging, is from studies of organic load-driven clogging in biogas slurry and algal matter studies, rather than from studies on FOG-containing kitchen effluent itself, which is a true and specific evidence gap that this review cannot fill. It was revealed that in many instances the substances that clog the porous ceramic emitters tend to gather at the water inlet, and that this clogging can be partially removed by flushing water with a low pH into the system (C. Yao et al., 2021)

Factors influencing clogging rate (wastewater quality, pore size, temperature)

Water quality is by far the most well-documented factor. The CT imaging study above has revealed that different poor-quality water sources

have very different clogging results; a clogging volume of 1.77 mm³ is generated with the Yellow River water in a clogging rate of 20% of the rated water flow. The salt water only causes an increase of clogging volume to 5.11 mm³ when the clogging rate reaches 50% of the rated water flow. The overall clogging situation is improved by blending the two water sources, compared with the single use of either source in the above study (Y. Yao et al., 2025). Then there's the chemistry of fertilizer applied to the emitter, an emitter with ammonified fertilizer applied via a wastewater stream could have a significantly higher sediment discharge capacity than the same emitter without fertilizer, which means the sediment load in an emitter is not the only factor affecting clogging risk, the chemistry of the fertilizer stream does too (Hou et al., 2024). A meta-analysis of labyrinth channel emitters under Yellow River water proved that water quality, flow-path geometry, and operating time are not independent but have interactions with each other; no single one of these parameters can be tuned independently to control clogging (Lv et al., 2024). The literature on ceramic emitters shows that smaller pore sizes are more effective at filtering the water but also plug more rapidly, but the ceramic emitter literature over the past decade has increasingly given preference to a narrow, deliberately targeted pore range, typically around 0 to 10 micrometers, because it will not allow root intrusion and soil suction caused by negative pressure to interfere with the delivery (Cai et al., 2021; Du et al., 2024). The literature on biofilms and water distribution does not provide specific information about the role of temperature in the growth rates of microbes, but from the general water distribution literature, it is inferred that the warmer the water, the faster the microbial growth rate. This is not a conclusion or a discovery, but a specific, definable gap, and the implications of any statement in the present review on the effect of temperature on kitchen wastewater-fed diffusers should be considered as a reasonable inference only, not as proof.

Detection and monitoring of clogging

The recent literature has presented three different strategies for detecting the violation, each with its own unique precision vs real-world considerations. Imaging-based is the most direct approach by employing X-ray CT scanning that enables researchers to visualize and quantify the

three-dimensional volume and distribution of clogging material within an emitter without destroying it, but such equipment is not available in a typical household and is far too expensive to use for a monitoring program. In the field literature the most common measure of clogging severity is hydraulic monitoring the relative average discharge rate (Dra) of an emitter, typically expressed as a percentage of the initial unclogged rate, as a function of time, without having to actually inspect the emitter (Aminpour et al., 2022; Wang et al., 2025). A third, less common method is based on the dry mass of clogging material collected from a disassembled emitter after a specified number of hours of use, which gives an actual gravimetric measurement of accumulation, rather than an indirect hydraulic “proxy” (Wang et al., 2025). All three of these approaches are poorly suited for continuous, unattended household monitoring, and here, the system design of this review comes back into the picture. The reference pot level sensing automation loop detailed above is, in fact, a very rudimentary form of indirect hydraulic discharge tracking, as a reduction in the frequency of refills on the entire network would imply a reduction in the rate of seepage from the diffuser pots. However, as already noted, this reference pot approach fails to differentiate between the cause of low seepage and is unable to pinpoint exactly which pot in a network is responsible, as a CT scan or per emitter Dra measurement would be able to do. Another concrete gap in the literature that this system will need to address is a low-cost, ‘household-viable’ method to detect clogs specifically.

Restoration methods: physical and mild chemical treatments

The most directly tested restoration method from the recent literature is physical flushing. A 2024 study evaluated lateral flushing for four different emitter geometries operating on high-sediment water, and found it to be an effective, though geometry-dependent, means of reducing the amount of accumulated clogging material, and found the percent of recovery to depend on the emitter design (Ma et al., 2024). A similar method is to remove sediment directly from the emitter flow channel rather than from the entire line, and further enhancement can be achieved by using a proper type of fertilizer, as the same research group has demonstrated that urea is capable of enhancing the capacity of the channel it

passes through to remove the sediment (Hou et al., 2024). Regarding the mild chemical treatments, magnetized water treatment, which does not require any added chemical at all, showed a reduction in clogging ratio of 1.97% at 1000 ppm salinity and 2.45% at 2000 ppm salinity, along with an increase in the average of emitter discharge by 2.7% to 5.6%, making it one of the mildest treatments tested in the recent literature (Abdelsalam et al., 2024). Reducing bacterial concentration and slowing clogging caused by biofilms has also been reported elsewhere in this literature through lower intensity chlorination instead of some of the more intensive chemical loads applied during certain conventional drip system maintenance protocols (C. Yao et al., 2021). Most importantly, none of the restoration methods reviewed in this subsection was tested with a kitchen wastewater or similar type of domestic greywater as the clogging material; all were tested on conventional pressurized drip or labyrinth emitters. The same goes for the ability to flush a buried clay pot, which in itself is quite different from the way a drip line is flushed, since there is no canal accessible within the clay pot that's under pressure to flush water through the sides of the pot, it is not obvious that flushing the sides of the drip irrigation system as mentioned in the literature would apply to this system reviewed here without a re-designed access point. Earlier studies strongly suggest the longevity of the diffuser material is not the primary factor rather, it is nearly all dependent upon water quality. The results from a controlled test revealed that effluent under unfiltered conditions completely clogged up to 83.3% of the emitters within 192 operating hours over 24 irrigation cycles in 10 weeks, with the poorest emitter type retaining only 14% of the original relative discharge (Aminpour et al., 2022). A separate 400-hour filtered, lower sediment load and fertilizer experiment, however, demonstrated only a 6.2% decrease in average discharge, while relative discharge stayed above 92% even at the highest tested sediment concentration (Wang et al., 2025). The distinction between these two outcomes, near total failure, and a single-digit reduction in failure rate over the same time periods, is virtually entirely due to the quality of the water being fed into the emitter, and nothing at all to any inherent properties of the emitter. The requirement for a pretreatment is screening, a grease trap, and multi-layer filtration, which is probably quite essential for the survival of the

clay pot diffusers in this review's proposed system, rather than a frivolous luxury. Meanwhile, even the most optimistic field evidence available (C. Yao et al., 2021) shows that clogging occurs gradually over a 2-year period as well, and some type of maintenance will be needed at some point, be it periodic flushing, mild chemical treatment, or just simple diffuser replacement.

IOT-BASED AUTOMATION FOR SUBSURFACE IRRIGATION

The role of IoT in the proposed system of this review is purposely small. The LPSPDIS described in the broad literature consisted of a single water level feedback loop, a reference pot at the same hydraulic level as all of the buried diffusers, with a bottom and a top water level probe, leading to a controller that switches a pump on and off. Four basic components are needed and the first is a pair of level probes at the bottom and top of the reference pot, either as simple float switches or as a pair of exposed electrodes that complete a circuit when they are submerged in water, which has been proven to work in small scale and household soil moisture and basin level irrigation controllers in the field (Pramanik et al., 2022). The latter is a microcontroller, as the others in the IoT irrigation literature that read a sensor, apply some threshold logic, and switch an output, exactly what it does here when the bottom probe is tripped, and the top probe means "stop" (Abdelmoneim et al., 2025; Vinod Kumar et al., 2025). The third one is a relay or small driver circuit, which is required as a microcontroller does not switch a pump's current directly, and it is common practice in all the low-cost automated irrigation controllers reviewed in this document. The fourth is the pump itself, which pumps into all of the diffuser pots simultaneously when it is triggered, since the working heads of the pump are relatively low, it does not need to be a high-pressure pump and so the cost and power draw is relatively low. For the type of domestic household kitchen garden environment in which this review is interested, the probes, microcontroller, and pump must be powered without mains electricity, a power supply, battery, or a small solar panel is required. While it would be nice to have it on the controller and allow it to report fill events or even for a fault to be remotely triggered, it is not necessary for the control loop and is really a convenience for

monitoring. The connections of these components are outlined in Figure 7. The probes supply the microcontroller with data; the microcontroller controls the relay, the relay powers the pump, and the power supply and optional connectivity module are in parallel with the main control path of the microcontroller. None of the four components mentioned here solves any of the genuine questions mentioned elsewhere in this review that are not solved by any of the components listed here, uneven clogging across a pot network, lack of a low-cost clogging detection method, and reliability of the shared level assumption across pots of different shape/size. In the LPSPDIS context, IoT should not be interpreted as a technology that alters the fundamental detection capabilities and/or diagnosis capabilities of the existing hydraulic and hardware system, but rather as a regulatory layer that is added to the existing hydraulic and hardware system.

Root-zone soil properties

Adhikary et al. (2021) investigated the performance of tomato irrigation using saline water with various irrigation water qualities and tillage systems and found that the irrigation water quality and tillage treatments significantly influenced soil properties such as pH, EC, organic carbon, and available nutrients (N, P, and K), with the highest fruit production, 49.79 fruits/plant and average fruit weight 61.77 g. Vasudaven et al. (2011) tested buried clay pitchers filled with saline water of three different dS.m^{-1} and saline water percolation ranged from 31% to 17% of the pitcher's capacity when the water salinity increased, compared with

the 43% percolation for non-saline water, the salt concentration was higher in the horizontal direction away from the pitcher, but lower when going down, indicating that the pitcher wall retains some of the salt. Likewise, approximately 10-liter clay pitchers of bottle gourd were used under freshwater and saline water irrigation, and by the saline water treatment, the highest soil ECe was 0.03 dS.m^{-1} and the soil pH was 0.2, while under freshwater irrigation the yield was $4.90 \pm 0.14 \text{ kg/pitcher}$ as compared to $3.96 \pm 0.125 \text{ kg/pitcher}$ under saline irrigation (Bazai et al., 2017). The available evidence, therefore, supports measurement of pH, EC, exchangeable Na^+/SAR , and available N-P-K in LPSPDIS experiments, but no reliable quantitative SAR value should be transferred from these studies because the clay pot literature does not provide a consistent SAR response.

Crop growth and water productivity outcomes

The crop growth and water productivity outcomes reported across clay pot studies using freshwater, saline water, and wastewater are summarized in Table 1. Earlier studies consistently report improved plant growth, yield, and water use efficiency under these systems compared with conventional irrigation methods. The evidence indicates that the clay pot system has the potential to significantly improve water productivity, and the two direct wastewater-fed studies indicate the feasibility of employing wastewater using porous clay systems. But, wastewater studies were conducted with general wastewater and treated dye wastewater, not

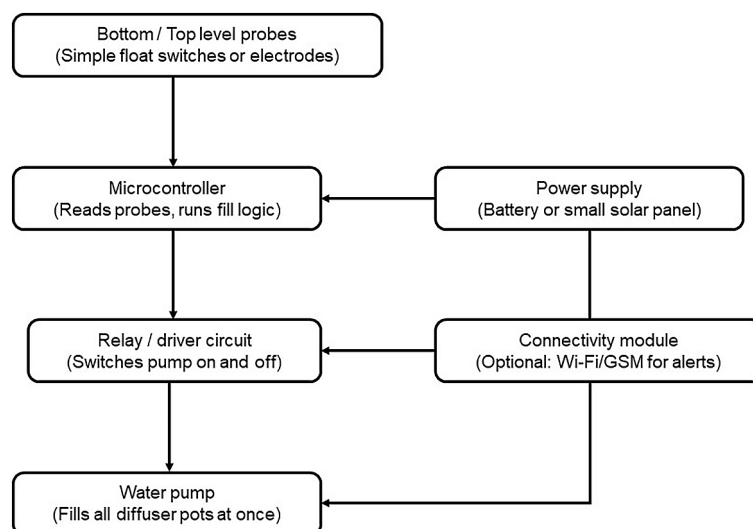


Figure 7. Basic IoT components required to regulate LPSPDIS

Table 1. Crop growth and water productivity outcomes

Crop	System	Water	Outcome	Source
Lettuce	Clay pot	Wastewater, 500 ml.day ⁻¹	Plant height 2.50 → 4.25 cm vs. 2.14 → 2.99 cm under watering-can irrigation	(Abubakari et al., 2011)
Tomato	Olla pot	Biosorption-treated dye wastewater	Adequate seepage for growth; COD removal 66.38 ± 1.58%, power density 2.23 mw.m ⁻²	(Man mohan et al., 2021)
Tomato	Clay pot	Freshwater	Water use 143.71 mm vs. 485.50 mm, WUE 33.62 kg.m ⁻³ vs. 6.67 kg.m ⁻³ , Fertilizer-use efficiency improved up to 52%	(Tefaye, Tesfaye and Woldetsadik, 2012)
Tomato	Clay pot	Freshwater	Yield increase up to 32%, water saving 41%	(Gebru et al., 2018)
Bottle gourd	Pitcher	Freshwater	Yield 4.90 ± 0.14 kg/pitcher, crop water productivity (CWP) 16.32 kg.m ⁻³	(Ahmed Bazai et al., 2017)

with screened wastewater from household kitchen waste. Bainbridge (2001) reported buried clay pot irrigation as a highly water-efficient method, with water use efficiency under some comparisons approaching 10 times that of conventional surface irrigation. Araya et al. (2015) compared different clay pot designs with bucket irrigation for Swiss chard and reported a maximum benefit cost ratio (BCR) of 3.27 for the best-performing imperforated clay pot treatment, indicating economic feasibility under the study conditions. Similarly, Gebru et al. (2018) reported approximately 41% irrigation water savings, together with yield increases of up to 32% for tomato under clay pot irrigation compared with furrow irrigation. In general, the evidence available confirms the status of clay pot irrigation as a high water productivity irrigation method, water savings of around 41% to 84% have been reported in a number of comparative experiments, and there is direct evidence on the use of wastewater, confirming the feasibility of irrigation with porous clay.

CONCLUSIONS

The above review shows that the technique of LPSPDIS can be considered to have great potential in making household vegetable farming more efficient. However, the combination of this technique with screened kitchen wastewater and IoT-based automated systems is not sufficiently proven. According to the earlier research conducted on clay pot systems, it has been shown that the technique has saved between 41% and 84% of irrigation water, 32% increase in tomato yield, and water use efficiency of 33.62 kg.m⁻³, compared with 6.67 kg.m⁻³ of furrow irrigation.

The greatest challenge is the deterioration of hydraulic function when wastewater is added to the system. Kitchen wastewater will most likely

have a higher organic load than other greywaters, but the studies done on clogging indicate that there will be a significant reduction in performance with low-quality water. In the evidence reviewed, the average flow rate reduced to 14% of the initial value for unfiltered wastewater versus 92.9% for filtered wastewater and fertilizer. It shows that filtration is important, but the influence of FOG and food waste present in household kitchen wastewater is not yet quantified on buried clay diffusers. Also, the IoT-based automation can be useful for simplifying the process, but the reference pot method that is being suggested can give only indirect data about the performance of the diffusers and cannot detect individual clogging issues. The agronomical and economic long-term performance is also unclear; multiple uses of wastewater, root zone dynamics, freshwater addition, energy input, maintenance needs, and payback period of the whole system are not well studied.

For that reason, the existing body of literature provides a base for technical feasibility but lacks validation of the complete system concept through the LPSPDIS. The next step which must be done before anything else is a multiyear experiment with both freshwater and screened kitchen wastewater in order to establish the relationship between seepage rate reduction, clogging process, yield, productivity of the water used, effect on the soil, savings of freshwater, energy consumption, and economic feasibility of the proposed solution.

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