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Review

Methods for Watering Seedlings in Arid Zones

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Abstract: This paper reviews different existing systems of seedling microirrigation in afforestation. These systems differ from agricultural irrigation methods since they only pursue the establishment of the planted seedlings instead of achieving good agricultural yields. They, therefore, involve very low irrigation doses compared to the usual irrigation doses found in the agricultural sector. These approaches are nonconventional localized irrigation systems with high efficiency in water application. Based on the water discharge equations they use, these methods can be classified into four groups: direct deep irrigation, irrigation through porous walls, irrigation with wicks, and irrigation with solar distillers. This paper describes a total of sixteen different systems suitable for afforestation. All the systems are compared with each other. To make the comparisons, four key parameters are considered: the cost of acquiring and installing the system, the water application efficiency, the maintenance of the system, and the possibility of irrigating several plants at the same time. The irrigation systems described in this review represent an important technical advance not only for dryland forestry but also for rainfed arboriculture, xeriscaping, and xerogardening. These systems make it possible to widely extend the planting period to almost throughout the year, not only in arid regions but also in less dry or even humid climates, especially when critical areas have to be afforested, including shallow, sandy, saline, or gypseous soils, suntraps, windy and desertified areas, open pit mines, and other areas. Seedling microirrigation is an emerging sector of the irrigation industry that is rapidly developing with new devices and patents. Two foreseeable future trends can be identified: the growing use of new permeable materials and the possibility of connecting individual emitters to irrigation lines.

Keywords: afforestation; stand establishment; failure avoidance; microirrigation; discharge equations; water application efficiency

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1. Introduction

The support irrigation and rescue irrigation of planted seedlings are both very useful approaches to reducing the number of failures caused by water stress in arid, subdesert, and desert areas [1–7]. These irrigation strategies are also very suitable for other critical areas for afforestation, such as places with shallow, sandy, saline, or gypseous soils, high windy areas, dry or south-facing aspects, abandoned open pit mines, or areas requiring restoration.

Irrigation makes it possible to extend the planting or sowing period and supplements traditional water harvesting techniques in afforestation [8–10]. In comparison with those techniques, its main advantage is being totally independent of the unpredictable rainfall in arid zones. Nevertheless, there are some limitations as well, e.g., its cost and the need for a reliable and sufficient water supply [11], which have to be accepted by local water users (mainly farmers). The water shortages inherent in arid and semiarid areas mean that, generally, seedling microirrigation should be mainly considered for small-scale tree planting projects rather than for more extensive areas.

An economic model comparing the option of replacement planting to maintain target density with the option of enhancing seedling survival from the beginning by applying irrigation was developed recently [7]. This model obtains the threshold value of seedling failure at which both alternatives offer the same economic result. The model can help foresters to make an informed decision about whether to irrigate seedlings or not.

Although conventional irrigation systems may be used (surface, sprinkler, or drip irrigation), nonconventional irrigation systems (NCISs) are frequently more advisable due to their lower water consumption rates. Their aim is quite different from that pursued in agriculture; their purpose is not to maximize production but to establish woody vegetation, i.e., trees and shrubs well adapted to the local forest site that, once established, thrive and develop independently. Therefore, features that are highly valued in agricultural irrigation (uniform emitting devices, pressure-compensating, self-cleaning, insensitivity to temperature changes, etc.) are of secondary importance compared with features such as low water consumption, high water application efficiency, pressureless flow rate, robustness and durability, or social acceptance.

Neither surface irrigation nor sprinkler irrigation systems are adequate for watering the small seedlings used in afforestation projects because the trees usually grow in low-density plantations, under water scarcity, and in locations with difficult access. Therefore, it is highly convenient to turn to localized irrigation systems. Furthermore, frequent surface irrigation may harm xerophytic plants as it favors the proliferation of root diseases [11]. Moreover, by moistening the whole soil, weeds and other unwanted plants have the opportunity to displace the seedlings. This is why operational forestry has tended not to use surface and sprinkler irrigation in favor of localized irrigation methods.

Despite their undeniable interest, the NCISs have so far received very little attention in the scientific literature. A simple Boolean query focused on the topic of this paper using the terms "afforestation" AND "irrigation" AND NOT "nursery" OR "drip" OR "sprinkler" OR "flood irrigation" focused on TITLE, ABSTRACT and KEYWORDS found 18 results in the SCOPUS databases and 239 in ScienceDirect (access: 10 July 2021). Significant parts of those papers are focused on the morpho-ecophysiological development of seedlings under irrigation [12,13] or the use of wastewater for irrigation [14]. Only a few papers show clear relevance to operational forestry, and the experiments were carried out in growth chambers. In this line, Al-Hawija et al. [15] show clear correlations between seedling survival and moisture regimes for *Cupressus arizonica* Greene in Syria. Similar results are presented by Versamis et al. [16] for *Fagus sylvatica* L. in Greece. Gao et al. [17] present a 10-year study on techniques for vegetation restoration in desertified areas in the Ulan Buh Desert (China), including irrigation. Unfortunately for our review, these authors use movable sprinklers, the technology not considered an NCIS in this review. In the same line, Rey-Benayas [18] assesses the growth and survival of holm oak (*Quercus ilex* L.) after irrigation. The only paper found with clear relevance to operational forestry is the silvicultural decision model by Del Río et al. [7]. A clear lack of scientific literature was evident, which has forced us to look for alternative sources, including professional communications, congress proceedings and abstracts, reports, local editorials, patents, websites, commercial catalogs, and technical and informative journals in different languages (English, French, German, Portuguese, and Spanish). In all likelihood, this lack of scientific studies will disappear soon because this issue is very relevant for the agroforestry sector, especially in the face of the consequences of climate change.

2. General Features and Discharge Equations of Nonconventional Irrigation Systems

The irrigation of planted seedlings in arid areas must fulfill certain features [19]. It must be localized (next to each plant), supplemental (watering only when necessary to ensure establishment), in deficit (mostly far from field capacity), and temporary (applied only during the first stages, until reaching hydric self-sufficiency). Water shall be applied at the subsuperficial level or under mulching (to avoid direct evaporation) and should be widely spaced in time (e.g., once a month or even once a year). These systems deliver water without requiring any pressure. As they only need a limited annual irrigation amount (usually less than 10 $m^3 \cdot ha^{-1} \cdot year^{-1}$) due to their localized application, their high water application efficiency, and the limited number of points per hectare to be watered (for instance, 1000 points per hectare), it is correct to talk about nanoirrigation and mini-irrigation doses.

In traditional irrigated agriculture, the irrigation dose is related to the water retention capacity of the soil (in the case of surface and sprinkler irrigation) or to the desired depth of the wetting front (in the case of drip irrigation). The aim is to obtain a good harvest. To achieve this, the crop should transpire as much as possible in order to maximize growth and yield. However, this strategy is not appropriate for xerophytic species, which are specialized in living under permanent or frequent water scarcity. During drought periods, they evapotranspire at a rate much lower than the potential evapotranspiration (*ET0*); let us assume the rate is half of *ET0*. A small seedling with a canopy of 0.02 m^2 and for a high *ET0* of 5 $mm \cdot day^{-1}$ only evapotranspires 1.5 L in a month (= $\frac{1}{2} \cdot 5 \cdot 0.02 \cdot 30$). Consequently, a small two-year-old seedling of *Pinus halepensis* Mill., *Pinus pinea* L., or *Quercus ilex* L. needs 1 or 2 liters of water per month in the summer. Therefore, just 2, 5, or (at most) 10 liter per seedling and drought season would be more than enough under Mediterranean climates [19].

When seedlings have to be established with the help of irrigation, a distinction should be made between first watering (immediately after planting or shortly afterward), support irrigation (scheduled watering to help seedlings overcome drought, maintained until the plants reach water self-sufficiency), and rescue irrigation (exceptional, not foreseeable watering implemented to save the seedlings from certain death due to an extreme drought).

Although microirrigation has been applied since the beginning of agriculture [20], the market for NCISs in operational forestry is quite new, offering an extensive range of systems that are described, classified, and compared in this review. Some of them are well known (e.g., buried clay pots or pipes stuck vertically into the soil), while others have only recently been developed.

Most NCISs include a water tank (Figure 1). In these cases, a small tank or cistern delivers water slowly and in different ways, without the need for hydrostatic pressure. The tank has to be refilled periodically either before or after it is completely empty (depending on whether the desired support irrigation should be continuous or intermittent). Some irrigation systems rely on the tank being filled by local vertical or horizontal precipitations. In these cases, they have a contributing area that allows them to collect the rainfall (Jaén® System), a surface area for rainwater and dew harvesting (Waterboxx®), or a fog collector to catch the fog droplets [21,22]. In this way, the number of water sources is increased, permitting the systems to become autonomous in certain locations so that they do not require regular refilling.

With regard to the water discharge system, four groups can be distinguished (Figure 1, Table 1): (a) direct deep irrigation (ruled by infiltration); (b) irrigation through porous walls (ruled by permeability); (c) irrigation with cords or felts (ruled by capillarity and permeability); (d) irrigation with solar distillers (ruled by evaporation and condensation).

The discharge equation of a conventional emitter (be it a traveling big gun, a sprinkler, microsprinkler, or a dripper) depends on the working pressure (h, in m) in the irrigation line [23]:

$$q = F_1(h) = k \cdot h^x \quad (1)$$

Here, q is the emitted flowrate {$L \cdot h^{-1}$}, h is the emitter's working pressure (m), k is its emitter coefficient {$L \cdot h^{-1} \cdot m^{-x}$}, x is the emitter exponent {unitless; with $x \geq 0$} and F_1 is a function symbol.

Contrary to this, the discharge equations that determine the flow rate of the emitters discussed in this paper do not depend on the working pressure. These emitters can work at zero-gauge pressure, i.e., h = 0 m (Table 1).

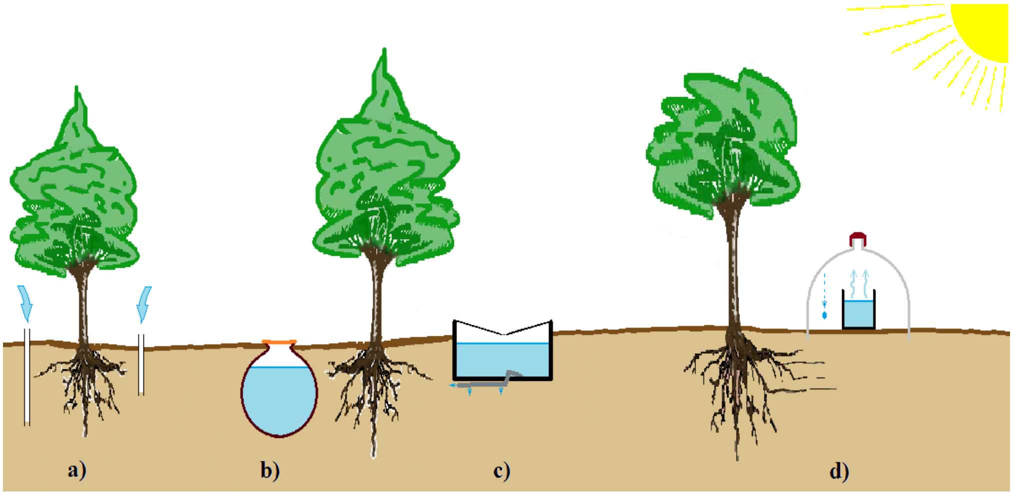

Figure 1. NCIS discharge systems: (**a**) direct infiltration; (**b**) porous walls; (**c**) irrigation wick; (**d**) solar distiller.

Table 1. Physical basis and discharge equations.

Irrigation System (Main Reference)	Physical Basis of the Flowrate	Discharge Equation [$q=F_i(x, y, z,\ldots)$]
Sprinkler, microsprinkler, or drip irrigation [23]	Working pressure (h)	$q = F_1(h) = k{\cdot}h^x$ (1)
Direct deep irrigation [24]	Infiltration (f)	$q = F_2(f, A) = c{\cdot}f{\cdot}A$ (2)
Irrigation through porous walls [25]	Permeability (k_{so}) and water potential (ψ)	$q = F_3(k_{so}, \psi, A, e) = c{\cdot}\frac{k_{so}}{e}{\cdot}\psi{\cdot}A$ (3)
Irrigation with felts or wicks [11]	Permeability (k_{sw}), water potential (ψ) and capillarity (I)	$q = F_4(k_{sw}, \psi, A, e, I)$ (4)
Irrigation with solar distillers [26]	Evaporation and condensation	$q = F_5(X, R_S, Op, T, ST) = c{\cdot}X^2{\cdot}ET0$ (5)

Note: The meaning of all symbols can be found in Appendix A.

3. Classification and Description of the Different NCISs

3.1. Direct Deep Irrigation

Direct deep irrigation consists of watering directly inside the soil. In these systems, the watering flow rate depends on the soil's infiltration capacity (f) and the area where the irrigation system contacts the soil (A). Although it is not applied to the surface, the water directly enters the soil so that, the same as in the case of surface irrigation, the flowrate (q) becomes proportional to the soil's infiltration capacity:

$$q = F_2(f, A) = c{\cdot}f{\cdot}A \quad (2)$$

Here, q is the emitted flowrate $\{L{\cdot}h^{-1}\}$; c is the discharge coefficient {unitless}, which adjusts the theoretical values to the real ones; f is the infiltration capacity of the soil $\{mm{\cdot}h^{-1}\}$; A the infiltration surface $\{m^2\}$; F_2 is a function symbol.

3.1.1. Microirrigation by Deep Pipes

This is a very effective, localized, and subsurface irrigation approach [27–29] where the watering is performed through a small vertical pipe of limited diameter (5 to 30 mm) buried 20 to 40 cm deep and raised 2 to 3 cm above the ground. Thanks to the vertical pipe, the water comes out deep in the soil, close to the seedling's roots. This method avoids wet or humid areas above ground and increases the efficiency in the application of water. PVC and PE plastic pipes and porous hoses can be used. Hollow stems of local plants (cane, bamboo, etc.) may be used as well and are environmentally preferable. There are also specific plastic pipes designed for this purpose available on the market, known as deep drip or deep pipe watering stakes, which, given the shape and material (reinforced top, pointed end, and made of hard ABS plastic), can be hammered directly into the ground (Figure 2).

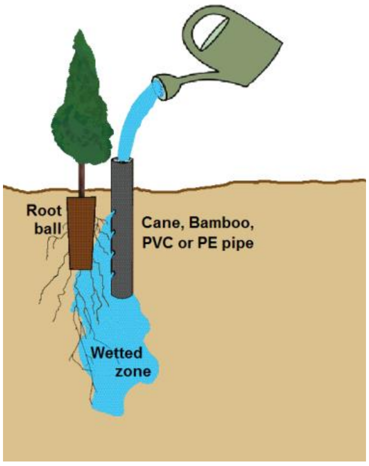

Figure 2. Subsurface irrigation with a deep pipe.

Irrigation can either be manual (filling pipe by pipe with a watering can) or through a network of irrigation lines with an emitter feeding each deep pipe. The latter is a type of subsurface drip irrigation that has a significant advantage—neither the roots nor the soil can interfere with the dripper's discharge [30].

Deep pipes are a simple, inexpensive, and efficient method of localized irrigation that promotes the growth of the seedlings' roots deep into the soil [31]. However, when applied to soils with extreme textures, it can show some limitations. In soils with high clay content, it may take an irrigation dose an extremely long time to reach its target (due to the very low infiltration rate). Only if the pipe is designed to receive the planned irrigation dose without having to wait for the water to infiltrate will the irrigation system work successfully. In contrast, soils that are very sandy have such low water retention capacity that the delivered water tends to percolate, escaping the seedling rhizosphere and being wasted. This problem can be solved by applying irrigation gels instead of water (Driwater®, Envirogrower®, etc.), although this solution is costly and more appropriate for xerogardening and arboriculture than for afforestation.

There are other subsurface irrigation systems that use vertical pipes. The so-called "buried stones pocket" [32,33] approach involves opening one or several trenches of adequate depth (0.5 to 1 m) next to the adult tree or seedling to be watered, leveling the bottoms, filling them partially with a layer of stones, covering the stones with a sheet of plastic, and covering the trenches with the extracted soil by inserting one or two deep pipes that connect the surface with the layer of stones. In this way, the irrigation dose can be applied quickly, even for soils with a low infiltration capacity. Water trickles horizontally and at the desired depth through the "pockets of buried stones". This method has been tested mainly in olive groves in Tunisia. It requires places where the soil is stony but deep.

Based on a similar concept, but more sophisticated is the "buried diffuser®" approach [34]. In this case, the layer of stones is replaced by a polyurethane emitter with a porous base that delivers water without the need for additional pressure (Figure 3). It is being tested on numerous fruit trees in Tunisia, Morocco, and France, including olive trees, date palms, pomegranate trees, almond trees, apple trees, pear trees, grapevines, and others.

"Irrigasc" [35,36] is a system developed in Senegal to plant trees and shrubs (mangos, cashew trees, orange trees, lemon trees, eucalyptus, papaya, and cassava). It consists of a pointed sock-shaped polypropylene mantle with holes and a rigid polyethylene (HDPE) section, which at one end has a rim in the form of a cup, with a capacity of about one liter

(Figure 4). After digging a hole of the same diameter (about 10 cm), the device, filled up to the base of the cup with the previously extracted soil or with an improved soil (adding NPK fertilizer, manure, compost, etc.), is inserted next to the seedling. Every few days, a liter of water is poured into the black cup of the mantle. The seedlings are watered over several months until the saplings reach hydric self-sufficiency.

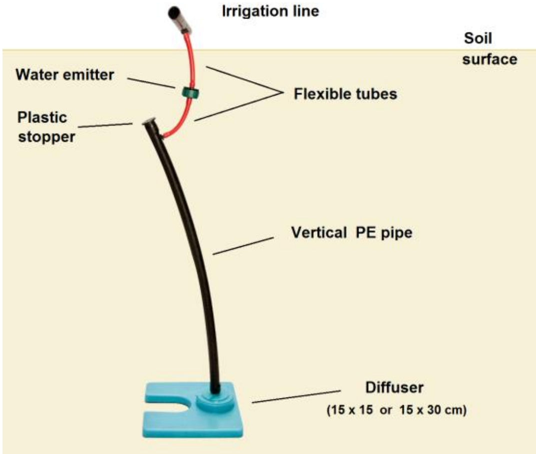

Figure 3. Diagram of the parts and connections of a buried diffuser®.

Figure 4. The "*Irrigasc*" permeable shaft.

3.1.2. Irrigation with Horizontal Perforated Pipes

This system is similar to the "buried stones pocket" approach, but with the peculiarity that it uses pipes similar to those commonly used for drainage [11,37]. These pipes have small drills or slots distributed over their surfaces through which water drains or infiltrates. The pipes are buried at the desired depth (about 30 to 50 cm or more). At an appropriate interval (between 15 to 30 m depending on the type of soil and the slope), a vertical filling pipe has to be installed, which may be the end of the drainage pipe itself. Usually, the pipe is filled either by a tank truck, a water tank transported by a farm tractor, or by an off-road fire truck. In order to measure out the dose properly, it is recommended to install a water counter in the hydraulic circuit of the tank. This way, it is possible to obtain a localized, subsurface, easy, and inexpensive irrigation method for linear plantations such as windbreaks in arid or hyperarid zones. However, this method is not suitable for rescue or support irrigation in extensive reforestation projects on rugged terrain or in sandy soils due to percolation.

3.2. Irrigation through Porous Walls

In irrigation through porous and saturated walls, the water supply is produced according to Darcy's law. The following discharge equation,

$$q = F_3(k_{so}, \psi, A, e) = c \cdot \frac{k_{so}}{e} \cdot \psi \cdot A \quad (3)$$

depends on four parameters, namely the surface of the porous wall (A), its permeability (k_{so}), its thickness (e), and the discharge potential (ψ), which represents the difference between the water potential on either side of the oozing wall, in the container and in the soil [25]. This last property (ψ) leads to self-regulation and allows an important saving of water [38,39]. It also results in variable irrigation doses on different spots of the same afforestation. However, this feature barely affects the final aim of the support microirrigation of xerophytic seedlings, which is their survival and establishment.

3.2.1. Irrigation with Buried Clay Pots

Irrigation with buried clay pots (pitchers) is both ancient and modern. It is ancient because mankind has been using it for over 2000 years [40–42], and it is modern because of its high efficiency and the renewed interest it has aroused today [43–51].

In Fang-Shengzi's book (written in Shandong, China, in the 1st century B.C.), this system is described when referring to the cultivation of melons [20]. According to Tilló [42], the Phoenicians buried porous clay pots close to olive trees and refilled them with water at regular intervals. The Romans are also familiar with this irrigation system and spread its use [40], which may explain why it is well known in Mediterranean culture and has been applied to the planting of fruit trees in arid places (olive trees, almond trees, carob trees, service trees, etc.). In Spanish forestry, this method is also applied and, significantly, is called "baby bottle" afforestation [52]. In countries such as Pakistan, Cuba, India, and Syria, this system is also used if the circumstances for afforestation are unfavorable [53–56].

The first systematic studies of pitcher irrigation were performed by Mondal [57] in Karnal (India) and Olguín [58,59] in Chapingo and Ciudad Obregón (Mexico). Mondal used isolated pots (to cultivate *Citrullus vulgaris* Schrad., *Cucumis melo* L., *Cucurbita pepo* L. and *Lagenaria leucantha* Rusby), while Olguín watered with ceramic capsules situated higher than the water source (Z) and interconnected with pipes. He successfully experimented with the cultivation of *Phaseolus vulgaris* L., *Vicia faba* L., and *Zea mays* L. (Figures 5 and 6).

These first studies have been followed by numerous research projects. Among them, those by Stein [60–65] in the field of agriculture and Bainbridge [11,28,41] in the field of ecology and forestry are the most outstanding.

Usually, the pots are filled manually, but methods of automatically refilling them through irrigation laterals and float valves have also been developed [65,66]. The use of closed porous capsules instead of open vessels curbs the risk of overflowing during refilling. Another option is to directly use porous pipes made of baked clay [37,44,67,68], a system that is adequate for watering linear windbreaks.

When irrigating xerophytic seedlings, burying a small recipient of baked clay (with a capacity 1 to 3 L) beside each plant and filling it periodically with water will guarantee the seedlings' establishment even in the most difficult places and conditions [11,53]. The essential feature of the recipient is its saturated hydraulic conductivity [43], a parameter that varies considerably depending on the type of clay used, the added components (sand, salt, or other), the cooking time and temperature, and the finishing of the pots' walls. This dispersion, which is very difficult to predict at the start of the manufacturing process in the potter's workshop, makes it advisable to perform tests before installing an extended pitcher irrigation system. For a recipient with a capacity of 2 L, an emptying time of three to four weeks is appropriate and allows to prolong the interval between fillings [19,25]. Regarding their shape, the best pots are those that are tall and have a narrow rim (narrow enough to cover them easily yet wide enough to allow refilling without water spillage), a long neck, and a big bottom (for deep root watering). The option of glazing the neck to improve its watering efficiency may be considered. Designs of this type include the Clayola and the Wetpot® systems created for gardening in arid regions.

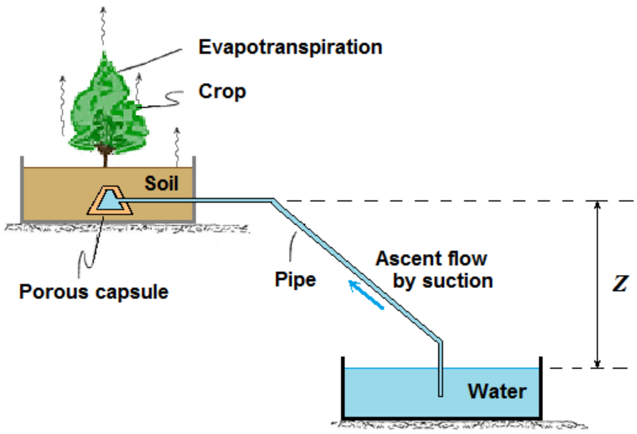

Figure 5. Pitcher irrigation system designed by Olguín [58].

Figure 6. Corn crop using pitcher irrigation with porous capsules connected to plastic pipes with a diameter of 4 mm. Picture of the first field tests, courtesy of Carlos Olguín Palacios.

3.2.2. Recycled PET Bottles with Fiber Filters

The option to water newly planted trees with buried and conveniently modified plastic bottles was successfully tested in Peru by Matorel [2,69,70]. His artisanal system called RIES (individual reservoirs for subsurface exudation) connects several bottles at their bottoms through small flexible tubing (to allow coordinated filling and emptying) and inserts small plastic fiber filters in the bottles (properly calibrated to deliver the stored water in about 25 to 30 days). The pack of bottles (with capacity ranging between 3 and 12 L) is buried next to the plant's roots, with only their caps visible above ground (Figure 7).

In Piura (Peru), afforestation projects with *Prosopis pallida* (H. & B. ex. Willd.) H.B.K., *Capparis angulata* Ruiz & Pav. ex DC., *Caesalpinea paipai* Ruiz & Pavón, and *Loxopterygium huasango* Spruce ex Engl. have been carried out. In the same region, fruit tree plantations of tamarind, mango, and ambarella (*Tamarindus indica* L., *Mangifera indica* L., and *Spondias cytherea* Sonn., respectively) have also been established using bigger emitters for more copious watering. Plastic bottles have also been converted into tree shelters to protect the seedlings from herbivory, wind, and drying up (Figure 8).

Figure 7. Individual water reservoir used for subsurface exudation (RIES) with two plastic fiber filters (red arrows). Picture: Mario Matorel García.

Figure 8. Handcrafted tree shelter and caps of the four bottles belonging to a buried RIES reservoir. Picture: Mario Matorel García.

The plastic bottles can be connected to an irrigation line in order to fill them simultaneously instead of one by one. Since 2011 an Australian company has sold porous bottles (Moistube Microreservoir®) of 1.5 to 3 L capacity meant to be installed in irrigation lines. These bottles require a low working pressure (h$\geq$ 2 m).

3.3. Wick Irrigation

An irrigation wick is a cord (a rope) of variable diameter and length made of synthetic (nylon, polyester, acryl, and others) or natural fibers (cotton, hemp, jute, etc.) that slowly absorbs, transmits, and discharges water. Its discharge equation (F_4) includes one more parameter than the equation for the oozers (3), the slope line (I) of the wick, but it has not been developed to date:

$$q = F_4(k_{sw}, \psi, A, e, I) \tag{4}$$

where k_{sw} is the saturated hydraulic conductivity of the wick {mm·h^{-1}}; ψ is the water discharge potential {m}, A is the transversal section of the wick {m^2}; e is the saturated length of the cord {m} (another segment of the cord remains unsaturated, where the discharge is ruled by the Buckingham–Darcy Law), and I is the slope line of the wick {in m/m; unitless}, which can be negative (descendant) {–}, positive (ascendant) {+}, or a combination of both {+,–} (Figure 9).

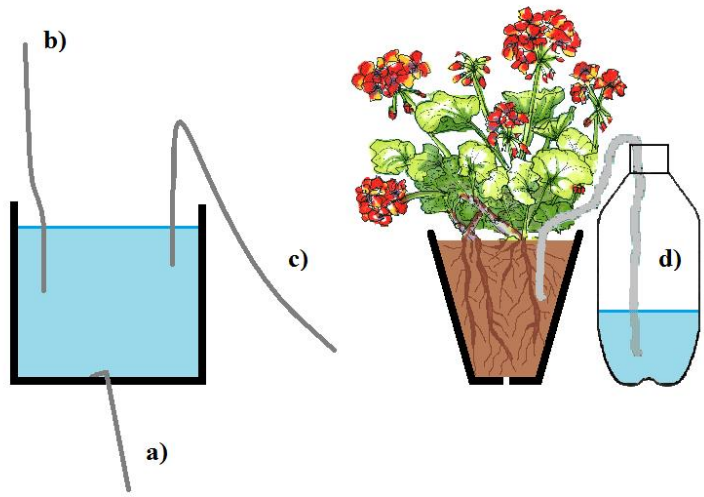

Figure 9. Slope line (I) of wicks: (**a**) downward (e.g., in the Waterboxx®); (**b**) upward (e.g., in the Wickinator®); (**c**) and (**d**) a combination of the two (capillary siphon); (**d**) typical domestic wick irrigation used for watering flower pots.

As with pervious walls, wicks have a flow rate that depends on the water content of the soil [71]. Their capacity to irrigate the subsurface, and do so in a self-regulated manner, makes them attractive [72,73], especially because they are inexpensive, hard-wearing, and easy to replace.

Bainbridge [11,28,37,74,75] has tested several different arrangements for the wick irrigation of seedlings. He recommends feeding the plant by gravity (downward wicks) and suggests the option of adding a hose clamp to regulate the flow rate as desired. With the aim of creating a superefficient irrigation system, the wick is placed into a PVC pipe to avoid water evaporation from the exposed part of the wick.

With a reused PET bottle and a wick of a slightly bigger diameter than that of the hole made in the bottle's cap (i.e., 8 and 7 mm, respectively), it is possible to set up a simple and inexpensive device to provide irrigation to seedlings during their first summer [76]. The part of the wick that is squeezed when passing through the hole in the cap acts as an emitter delivering water to the remaining part of the wick, which transmits the water to the soil and helps the saplings take root. In some regions of India, pitcher irrigation is combined with the use of wicks [77]. In this way, the water flows directly to the shallow rhizosphere, and at the same time, the penetration of water into the soil through the wick is promoted. In the Indian states of Karnataka and Kerala, this combined irrigation system is applied during the first two or three years when planting coconut trees (*Cocos nucifera* L.) and betel palms (*Areca catechu* L.) [78,79] (Figure 10).

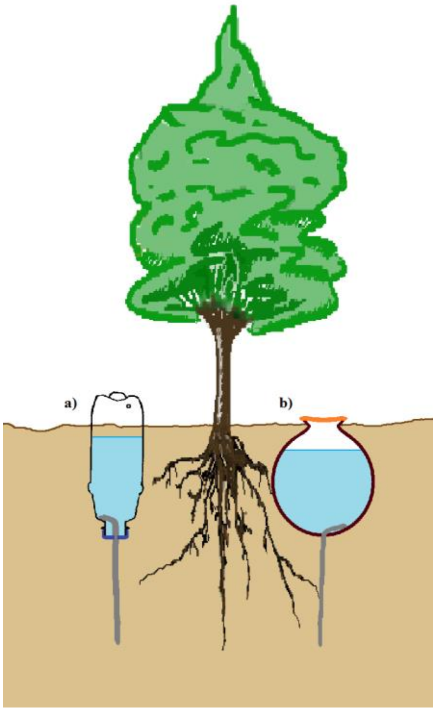

Figure 10. Discharge reservoirs with wicks: (**a**) PET bottle; (**b**) clay pot.

Today, two systems related to the microirrigation of seedlings via slow irrigation through wicks or felts are available on the market: the Eco Bag® and the Waterboxx®. The first system was developed in 2005. It is a plastic bag with a shape resembling a neck pillow (Figure 11). It has a capacity of 20 L, covers a surface of 0.6 × 0.6 m^2 around the plant, and discharges water through felt at a rate of about 1 L·day^{-1}. If continuous irrigation is desired, the bag has to be refilled every three to four weeks. The bag is placed on the surface but is easily hidden under straw, wood chips, or earth (leaving the filler cap uncovered). The device is being used to plant seedlings in xerogardening and afforestation systems in Queensland (Australia).

Figure 11. One-year-old *Quercus ilex* seedling irrigated with an Eco Bag®.

A more sophisticated product is the Waterboxx®, developed in 2008. It consists of a polypropylene bucket with a slightly cone-shaped cylinder that surrounds and protects the seedlings or seeds it contains. Inside the box is a reservoir with a capacity of about 15 L. The center of the box is hollow, giving the plants space to grow, while the water is delivered by a wick that is threaded to the bottom. The hollow at the center of the box has the form of an "8" (Figure 12) to allow the growth of two seedlings. The box has two lids: an intermediate insulating plate and a funnel-shaped ribbed superior lid with a filler cap. Rainwater is collected through the funnel and canalized to the bottom of the box via two small downspouts. Under certain weather conditions, the ribbed funnel (which is somehow reminiscent of a lemon squeezer) can act as a dew condenser so that the system maintains substantial hydric self-sufficiency, even in the adverse conditions of a prolonged drought. Even without the contribution of rain or dew, microirrigation is guaranteed for several months as the flow rate through the wick is less than 0.3 L a day. The box also serves to eliminate the competition of invasive species and acts as a mulch, preventing direct evaporation of the damp soil and tempering the ground [80]. It must be installed on the bottom of a small pit with a totally horizontal base that has been prepared during plantation or sowing. The box should stick a few centimeters out of the soil surface, should be properly fastened, and should be firmly anchored in the ground. Once it is installed, it must be filled with about 15 L of water. The box is lightweight but robustly constructed so that it can be used several times (it has a lifetime of approximately ten years; it must irrigate a planted seedling for one or two years, then it is carefully removed and can be used with another seedling). In addition to the original polypropylene model, other prototypes made of biodegradable materials and with a smooth funnel are being tested, which may possibly reduce the price. The Waterboxx® was introduced by the inventor (Pieter Hoff) in more than 25 countries.

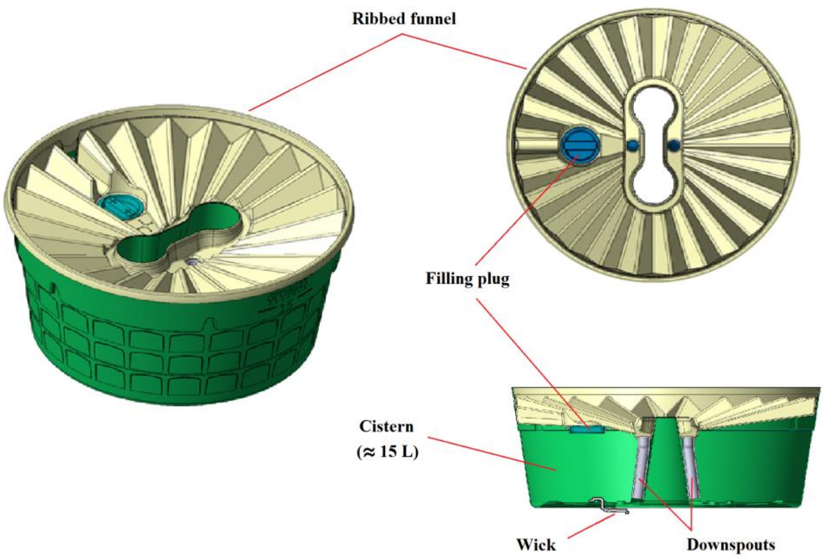

Figure 12. Perspective view, plan view, and radial section of a Waterboxx (©AquaPro).

3.4. Irrigation with Solar Distillers

Solar distillation makes it possible to obtain fresh water from vegetal material, polluted water, or saltwater. This water is drinkable [81,82] and can also be used for watering plants in greenhouses [83–86] or in fields. Regarding the latter, Howard [87] patented an irrigation system with solar distillers in 1972. In 1981, Maldonado [88] successfully established a peach tree plantation in a desert area called Ramos Arizpe in Coahuila, Mexico. He used chopped cacti (*Opuntia* sp.) to obtain water via solar distillation. The chopped cacti were placed in an excavated hole next to each sapling and covered with a polyethylene sheet. The vegetal material rested either directly on the ground or on a container furnished with a hosepipe that delivered the condensed water to the tree's root ball. Constantz [89,90] proposed and patented a solar irrigation system for crops planted in well-spaced rows (orchard crops, vineyards, etc.). Between the rows, he installed impervious black plastic sheeting, which served as a container to store the water to be distilled. Over this cover, he placed another roof-shaped cover of transparent plastic, from which the drops of condensed water slipped down to the crop row. In 1996, Ishimoto [91] patented a similar irrigation system, also meant for orchard crops (Figure 13a,b). Another use for solar distillers was proposed by Sinha et al. [92], in this case, to remove salt from the root zone to leach saline soils in desert areas prior to the plantation. This solar distillation device is built from three assembled PET bottles.

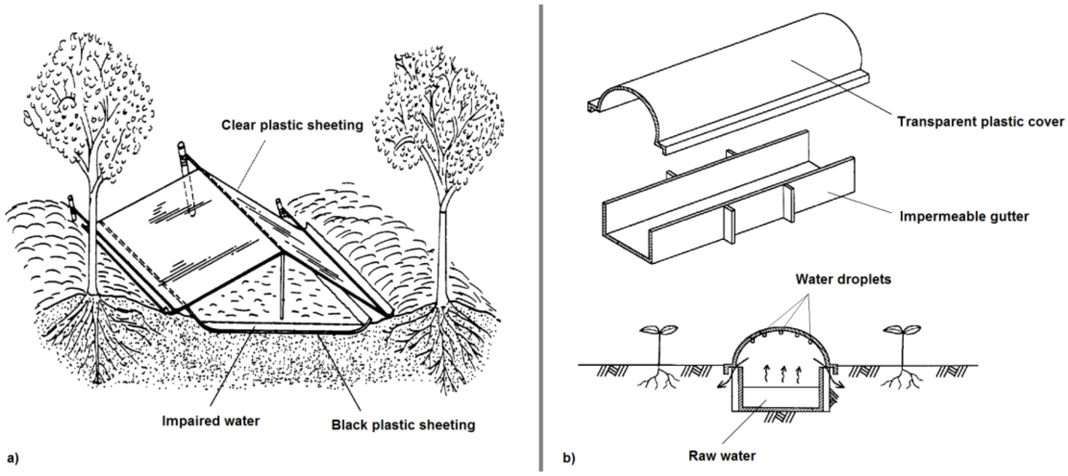

Figure 13. Solar stills for watering crops: (**a**) system invented by Constantz [90]; (**b**) system invented by Ishimoto [91], redrawn from original figures of the patents.

A simpler system that is more practical and suitable for afforestation was designed by Leimbacher [93], called the kondenskompressor system (Konkom in short). The Konkom emitter consists of two used plastic bottles of different sizes (e.g., one with 5 L and another 1.5 L capacity) assembled as shown in Figure 14. The base of the bigger bottle is cut out, while the smaller bottle is cut in half. The container resulting from the smaller bottle is filled with water and placed next to the plant to be watered. Over it, the big bottle should be placed as if it were a bell jar, centered, and stuck a few centimeters into the soil. It is essential that the placement of the two bottles permits the cap of the bigger bottle to be opened in order to fill water into the smaller one.

In this enclosed space, the hydrologic cycle takes place in a simplified manner and on a small scale. The water evaporated by the sun condenses on the ceiling, the walls, and the bottom of the enclosure, which, in this case, is the area of the soil to be watered (Figure 14). The general discharge equation is:

$$q = F_5(X, R_S, Op, T, S) = c \cdot X^2 \cdot ET0 \quad (5)$$

where X is a characteristic length that describes the distiller's size {m}, R_S is the solar radiation (irradiance) received by the emitter {$W \cdot m^{-2}$}, Op are the optical properties of the Konkom's outer bottle (light reflection, transmission and absorption) {$W \cdot m^{-2}$}, T is the air temperature {K}, S reflects the soil type (mainly granulometry and porosity) {m}, c is the Konkom's discharge coefficient {unitless; $c < < 1$} and ET0 is the potential evapotranspiration {mm·day-1}.

The Konkom device has been tested on vegetables (tomatoes, beans, and squashes, among others), but it could be useful for afforestation, too. The device provides watering at no cost and is synchronized with the plant's needs because the watering becomes more intense when the sun shines brightest on the distiller, i.e., when the plant transpires most [19]. Even if the watering takes place in the middle of the day, very little water is lost by direct evaporation, as the water not transpired by the plant remains inside a semiclosed circuit of evaporation and condensation and does not leave the solar distiller. In order to better ensure the efficiency of the water use, mulching of the soil around the Konkom device and the plant (with straw, stones, etc.) is advisable so that no moist surface is left exposed.

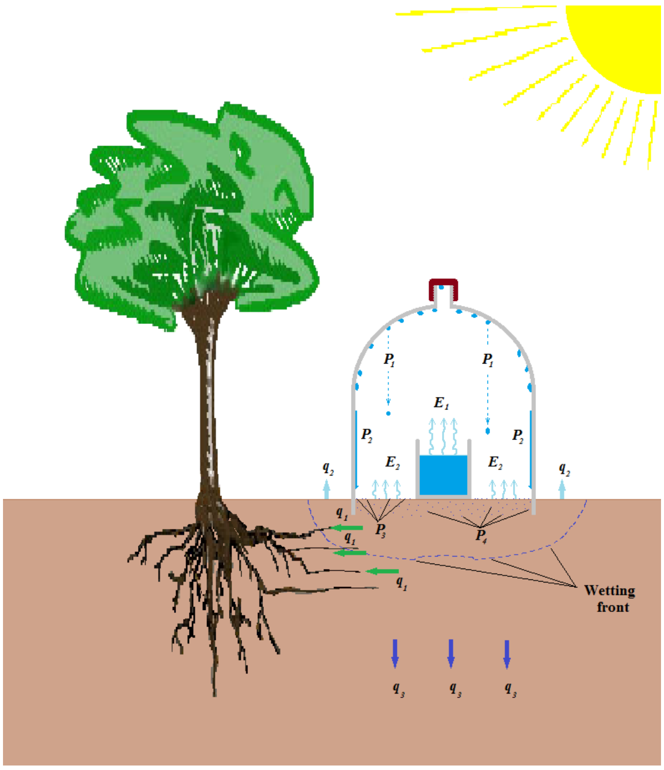

Figure 14. Arrangement of a Konkom device with its two modified bottles and specifications of some parameters and variables that explain its function (see the text below).

The results of the first tests were promising. The annual amount of irrigation can be diminished to a tenth of the volume used by traditional irrigation systems for vegetable gardens, and similar yields can be obtained [93]. Furthermore, it is remarkable that this system allows the use of brackish or even seawater because the sun will transform it into freshwater. The technical problem to be solved is to determine how many emitters are needed to irrigate a particular plant with specific water needs. The first results have shown that, with four distillers consisting of an outer 5 L bottle and an inner bottle of 1.5 L, a good yield can be obtained in vegetable gardens [93]. Therefore, it can be deduced that, for the support irrigation of xerophytic seedlings, one distiller (5 L/1.5 L) should suffice.

The Konkom device irrigates the soil by means of vertical precipitation (dripping from the dome [P_1] and down the walls [P_2]) and horizontal precipitation (the dew that settles directly on the ground's surface [P_3] and the occult precipitation, i.e., the condensation inside the soil [P_4]).

In the interior of the emitter, a nearly closed circuit of evaporation (E_1, E_2) and condensation (P_1, P_2, P_3, P_4) on the different parts of the distiller takes place; hence the German name Kondenskompressor. Only the moisture absorbed by the roots (q_1) and the moisture that reaches the outside of the bigger bottle (q_2) escapes this circuit. Additionally, some of the water discharged by the Konkom may escape the rhizosphere and percolate (q_3), especially on long and sunny days in sandy soils (Figure 14). The two latter terms (q_2 and q_3) should, of course, be as small as possible (zero) so that the value of the water application efficiency is close to one.

$$q = q_1 + q_2 + q_3 \tag{6}$$

The careful maintenance required by this emitter, as well as its fragility, make it suitable for watering small stands. Should the fauna be abundant and salty or brackish water be used, fencing is recommended to avoid spilling water close to the seedlings. A recent iteration of the Waterboxx®, the Waterfilter Boxx®, includes solar distillation. This is a robust box, unlike the Konkom device.

4. Comparison of Irrigation Systems

It is useful to distinguish between first watering, rescue watering, support irrigation, and growth and yield irrigation. The first watering is not necessary by choosing the appropriate planting season; that is, working on slightly damp soils and expecting some rain in the foreseeable future. In this review, growth and yield irrigation are not discussed, as this type of irrigation is for arboriculture, cultivation of fruit trees and fruit bushes, vineyards, truffle cultivation, or gardening. This paper focuses on supporting irrigation and rescue watering in the context of afforestation. Support watering has to be included and programmed in the afforestation project (watering system, irrigation months, irrigation frequency, irrigation dose, years of irrigation, daily wages, and required equipment). Unexpected rainy periods may cause a reduction in or even the suspension of irrigation (and subsequently reduced water consumption, which is convenient in drylands). On the other hand, prolonged or unseasonal drought may make it necessary to increase the initially estimated support watering. Although rescue watering periods are performed in emergencies, this does not mean they should be improvised. To forestall the consequences of an abnormal and prolonged drought that could put at risk the seedlings' survival, the irrigation system, the water dose for each seedling, the total quantity of water required, the materials and the human workforce, as well as the duration of the works, should be planned. When afforesting dry areas, one must be prepared for these adversities and know how to approach them, i.e., must know how to water seedlings efficiently.

In the following, tree pit irrigation will serve as the reference irrigation system. This watering system involves digging a small pit around every seedling and periodically filling it up with water. The volume of the hole, its location with respect to the seedling, the irrigation dose, and the watering frequency must be established by the project designer. The pit capacity (CAP, in L) and the irrigation dose (D, in L) are related, as the volume of water of each watering phase must not exceed the capacity of the pit (CAP $\approx$ D). In turn, the irrigation dose has to remain in the soil at a similar (or slightly deeper) depth (p, in m) to the seedlings' rooting depth (D $\approx$ AWC$\cdot$p$\cdot$S), with AWS being the water retention capacity of the soil (in mm$\cdot$m^{-1}) and S being the pit's surface (in m^2). A higher dose would be a waste, as the water would be lost to deep percolation. However, a lower irrigation dose (less than 10 L$\cdot$seedling^{-1}) would be inefficient, given the fast evaporation of water near the soil's surface. Allen et al. [94,95] point out that the initial evaporation rate (E) of bare soil after irrigation is 15% higher than the potential or reference evapotranspiration (E $\approx$ 1.15$\cdot$ET0), and that such an accelerated evaporation process may last several days (as an example, within only two days for an ET0 of 5 mm$\cdot$day^{-1}: E $\approx$ 1.15$\cdot$5$\cdot$2 = 11.5 mm). To partially circumvent this problem, high doses of irrigation have to be applied (15 L$\cdot$seedling^{-1} or more). In this way, quite a large quantity of the water penetrates deep enough into the soil and escapes direct evaporation. To reduce evaporation, the soil in the pit should be covered with a layer of dry soil or with stones immediately after watering. This improves the efficiency of the irrigation, although at the expense of labor efficiency. Thus, the tree pit irrigation system is conditioned by soil (humidity should not escape the rhizosphere) and climate (high evaporation rates). In many environments (shallow soils, sandy soils, hot climates, and low relative humidity), there remains only a small margin for efficient tree pit irrigation. Add to this that the minimum irrigation dose (about 15 L$\cdot$seedling$^{-1}\cdot$irrigation^{-1}) and the frequency (an irrigation every few weeks) are high, it seems clear that nonconventional irrigation systems (NCISs) offer an interesting alternative.

Today, off-road vehicles and tractors equipped with tanks and pumps make water transport in rugged terrain easier. Firefighting equipment could also be used, although it would have to be adjusted to be able to work simultaneously with several hoses, at low pressure, and with a flow rate, valves, and nozzles that allow fast and safe filling of the irrigation system without spilling water. In the discharge circuit, a volumetric counter should be included to ensure adequate control of the applied water volume. Even with this type of motorized equipment, the transport of water to the seedlings remains a challenging, slow, and costly task, especially in rugged terrain located far from a water source. Therefore, irrigation systems should be chosen that require few refills per season (preferably only one) and little water. The most convenient NCIS for a given situation can be chosen by taking into account the capacity of the water tank and the watering flow rate. If only brackish or salty water is available, solar distillers are the only option (Konkom, Waterfilter Boxx®). To avoid water loss by percolation in sandy or shallow soil, the water delivery has to be gradual; that is, managed by the irrigation system itself. In these situations, porous walls and wicks are recommended. However, for soils with good water retention capacity, it is possible to opt for less expensive irrigation systems such as vertical deep pipes or horizontal perforated pipes. In the case of vertical deep pipes driven into clayey soil, the diameter of the pipes must be carefully chosen so that the dose can be delivered without having to wait for the water to infiltrate. See additional recommendations in Table 2.

Table 2. Some advice for watering seedlings in arid zones *.

Topic	Advice
Site preparation	(1) Deep soil cultivation. (2) Layout water harvesting systems to concentrate surface runoff and infiltration next to the seedlings. (3) Irrigate if both aforementioned measures are not sufficient.
Water availability	(1) If scarce: deficit irrigation systems with high water application efficiency; NCISs. (2) If abundant: Deep pipes; tree pit irrigation.
Difficult access to afforestation site	(1) Choose an NCIS that needs only one filling during the dry season. (2) Tank and emitter must be designed for this purpose. (3) Very low irrigation frequency, though not necessarily intermittent watering.
Performance	(1) To reduce costs, it is advisable to install the NCIS when planting. (2) Results improve with joint irrigation. Approximate figures for individual irrigation: 20 seedlings·h^{-1}; 0.20 ha·$workday^{-1}$ for a plantation density of 800 seedlings·ha^{-1}).
Sandy or shallow soils, with low water retention capacity	Systems with water storage and slow water delivery through porous walls or wicks: pitchers, porous capsules, PET bottles with wicks, Waterboxx®, and similar).
Deep loamy, silty, or clayey soils, with good water retention capacity	(1) An inexpensive NCIS can be chosen. (2) Tree pit irrigation and deep pipes are the most inexpensive options.
Windbreak	(1) On soils with good water retention capacity, horizontal perforated pipes buried at a depth of 30 to 50 cm are a good option. (2) For sandy soils, other solutions have to be chosen: e.g., porous pipes of baked clay.
Water quality	(1) Non filtered, murky, turbid waters: use systems that do not easily clog; avoid wicks, diffusers, fiber filters, drip irrigation emitters. (2) Waters with a high salt content: continuous soil watering (through wicks or porous walls) is preferable to intermittent or sporadic irrigation. (3) Brackish or salty waters: irrigation is only possible using solar distillers: Konkom, Waterfilter Boxx®.

* Basic data: (1) Surface (number of seedlings to be irrigated); (2) Quantity and quality of the available water; (3) Cost of the irrigation system; (4) Time needed for single irrigation; (5) Technical means and wages needs; (6) Irrigation dose; (7) Irrigation frequency ; (8) Cost of a single irrigation.

A comparison between the different irrigation systems is shown in Table 3, including the tree pit irrigation system as the reference system. To gain a general overview and to make the comparison, four key parameters are considered: the cost of acquiring and installing the system (C_a), the water application efficiency (E_a), the maintenance of the system, and the possibility of irrigating several plants at the same time. The last column in Table 3 gives some general indicators of each method, which can be expanded upon by reading the specific section.

Table 3. Comparison of different seedling irrigation systems (NCISs).

System (Main Reference)	Physical Basis	Cost (EUR·unit^{-1})	Water Application Efficiency	Maintenance	Usage	Comments
Tree pit irrigation	Infiltration	Very low (0.46)	Low	Low	Individual	Reference irrigation system
Deep pipes [11]	Infiltration	Low (0.56)	Medium	Low	Individual	Very easy and efficient system
Irrigasc [35]	Infiltration	Medium (1.54)	Medium	Low	Individual	System appropriate for arboriculture
Buried diffuser® [34]	Infiltration	Very high (3.91)	High	Medium	Joint	System appropriate for arboriculture
Horizontal perforated pipes [11]	Infiltration	Very high (3.74)	Medium	Low	Joint	Good solution for windbreaks
Buried stones pocket [32]	Infiltration	Medium (1.65)	Medium	Low	Individual	Appropriate for arboriculture on deep, clayey soils
Buried pitchers [41]	Water potential	Medium (1.94)	Very high	Medium	Individual	Traditional "baby bottle" afforestations
Porous capsules [37]	Water potential	Medium (1.16)	Very high	Medium	Joint	Good emitters for subsurface drip irrigation
RIES bottles [69]	Water potential	Medium (1.58)	Very high	Medium	Individual	Method similar to pitcher irrigation
Moistube Microreservoir® [19]	Pressure and water potential	Very high (4.26)	High	Medium	Joint	Appropriate for arboriculture. Requires some working pressure
PET bottles with wicks [76]	Water potential and capillarity	Low (0.95)	Very high	Medium	Individual	Easy and efficient artisanal system
Pitchers with wicks [77]	Water potential and capillarity	High (2.51)	Very high	Medium	Individual	Combined system
Eco Bag® [19]	Water potential and capillarity	Very high (4.11)	Very high	High	Individual	System appropriate for xeriscaping and arboriculture.
Waterboxx® [19]	Water potential and capillarity	High (2.75)	Very high	Medium	Individual	The box can be reused up to ten times.
Konkom [19]	Solar distillation	Low (0.85)	High	High	Individual	Possibility of using brackish or saltwater. Fragile
Waterfilter Boxx®	Solar distillation	High (3.05)	Very high	Medium	Individual	Possibility of using brackish or saltwater. Robust

Table based on published data [7,11,19] and information provided in this paper and by the manufacturers of each product.

The cost for digging a small pit (approximately 0.3 m^2 in area and 0.1 m deep) around each seedling has been estimated at EUR 0.46 per unit for an hourly wage of EUR 5.50. The costs (C_a) for the other systems have been obtained from prices provided by manufacturers, consulting craftsmen (potters), or adding the unit prices of the different materials needed to set up the system (wicks, bottles, clay pots, drills, fiber filters, etc., in the case of handcrafted systems) (Table 4). The time needed for implementation and installation has also been considered. For the Waterboxx® and Waterfilter Boxx®, a quintuple use is estimated due to their robustness (although the manufacturer extends its durability to ten years if wicks are changed annually). To equalize values, import costs are not considered. The reference country used for obtaining the costs is Spain. To transform these costs to those of another country, the data can be converted to international dollars (Geary–Khamis dollars, GK) using the purchasing power parity of Spain and of the desired country at a given time.

Table 4. Acquisition and installation costs of different irrigation systems.

System	Materials	Handmade Production	Installation	Total Cost (C_a) (EUR·unit^{-1})
Tree pit irrigation	–	–	EUR 0.46 (5 min per pit)	Very low (0.46)
Deep pipes	EUR 0.10 (0.5 m PE pipe, 30 mm diameter; used 5 times)	EUR 0.09 (1 min; pipe cutting)	EUR 0.37 (4 min per pipe)	Low (0.56)
Irrigasc	EUR 0.10 (plastic bag), EUR 0.49 (rigid cup), 0.12 EUR (6 L of enriched soil)	EUR 0.28 (3 min; bag to cup welding)	EUR 0.55 (6 min per Irrigasc)	Medium (1.54)
Buried diffuser®	EUR 3.0 (diffuser), 0.45 EUR (3 m PE pipe, 16 mm diameter)	–	EUR 0.46 (5 min per diffuser)	Very high (3.91)
Horizontal perforated pipes	EUR 1.74 (1.00 m drainage PVC pipe, 100 mm diameter) [1]	–	EUR 2.00 (backhoe + 2 workers; EUR 50 ·h^{-1}; pipe buried 50 cm deep; 25 m installed in 1 h)	Very high (3.74) [1]
Buried stones pocket	EUR 0.50 (0.5 m PE pipe, 30 mm diameter), EUR 0.05 (1 m^2 plastic sheet)	–	EUR 1.10 (1 m trench per seedling, 0.5 m deep; 10 seedlings·h^{-1}; 2 workers)	Medium (1.65)
Buried pitchers	EUR 1.48 (2 L clay pot)	–	EUR 0.46 (5 min per pitcher)	Medium (1.94)
Porous capsules	EUR 0.70 (0.5 L capsule), EUR 0.09 (3 m PE pipe, 16 mm diameter; used 5 times)	–	EUR 0.37 (4 min per capsule)	Medium (1.16)
RIES bottles	EUR 0.04 (4 reused PET bottles), EUR 0.04 (material for 4 fiber filters), EUR 0.03 (3 mini tubings)	EUR 0.92 (10 min; heat sealing of filters and tubings to the bottles)	EUR 0.55 (6 min per RIES)	Medium (1.58)
Moistube Microreservoir®	EUR 0.48 (1 reservoir), EUR 0.45 (3 m PE pipe, 16 mm diameter)	–	EUR 3.33 (backhoe + 2 workers installing bottles and pipes buried 30 cm; EUR 50·h^{-1}; 45 m installed in 1 h)	Very high (4.26)
PET bottles with wicks	EUR 0.01 (1 reused PET bottle), EUR 0.20 (0.4 m nylon wick, 8 mm diameter)	EUR 0.37 (4 min; drill, knot, and threading, bottle cap closing)	EUR 0.37 (4 min per bottle)	Low (0.95)
Pitchers with wicks	EUR 1.48 (2 L clay pot), EUR 0.20 (0.4 m nylon wick, 8 mm diameter)	EUR 0.28 (3 min; knot and threading)	EUR 0.55 (6 min per pitcher)	High (2.51)
Eco Bag®	EUR 3.74 (used 2 times)	–	EUR 0.37 (4 min per bag)	Very high (4.11)

Table 4. *Cont.*

System	Materials	Handmade Production	Installation	Total Cost (C_a) (EUR·unit[-1])
Waterboxx®	EUR 2.20 (used 5 times)	–	EUR 0.55 (6 min per box)	High (2.75)
Konkom	EUR 0.02 (2 reused PET bottles)	EUR 0,28 (3 min to trim the bottles)	EUR 0.55 (6 min per Konkom)	Low (0,85)
Waterfilter Boxx®	EUR 2.50 (used 5 times)	–	EUR 0.55 (6 min per box)	High (3.05)

Remarks:

- Costs in Spain in euros (EUR); the year 2021.
- Hourly wage: EUR 5.50
- Reference plantation density: 1111 seedlings·ha^{-1} (spacing: 3 × 3; 3 m pipe per plant).
- [1] Horizontal perforated pipes: Windbreak with 1 row, seedlings equidistant 1.00 m. Barriers spaced 100 m (100 m in length to cover one hectare). 1.00 m pipe per plant.

For an operational comparison of NCISs, the following intervals are established:

- Very low cost: C_a < EUR 0.50;
- Low cost: 0.50 ≤ C_a < EUR 1.00;
- Medium cost: 1.00 ≤ C_a < EUR 2.00;
- High cost: 2.00 ≤ C_a < EUR 3.50;
- Very high cost: C_a ≥ EUR 3.5.

The water application efficiency (E_a) is obtained by dividing the water volume retained in the rhizosphere to meet the seedlings' water needs (V_b) by the water volume applied by the irrigation system (V_a): $E_a = V_b/V_a$. This value depends on numerous factors, including the irrigation system, soil, climate, plant species, and handling of the system. A qualitative classification of the efficiency can be established, focusing on the two main variables that reduce E_a: direct evaporation (E) and percolation (DP).

- Very low/low efficiency: when E and DP are not controlled ($E_a < 0.60$);
- Medium efficiency: one of these two variables is controlled;
- High efficiency: both variables are controlled;
- Very high efficiency: E and DP are avoided ($E_a \geq 0.95$).

If the correct installation of the NCIS is assumed, the roots of the seedling can easily find the humidified soil. It is also assumed that the system is being handled correctly. Direct evaporation will be minimal for buried systems or if the humidified surface lies under the system itself or is protected by mulch. To prevent percolation, the doses applied must be adjusted to the water retention capacity of the seedlings' rhizosphere. Under these premises, NCISs can match or even beat the E_a of subsurface drip irrigation. In irrigation systems with horizontal perforated pipes, limited water percolation is inevitable at those stretches of the pipe closer to the water source or at the deepest parts of the pipe route. A similar limitation can be inferred for other NCISs that use the soil to store water. Instead, NCISs that perform high-deficit subsurface watering by regulating the flow rate through porous walls or wicks are the most efficient. Taking into account these general considerations, an estimated efficiency rate can be assigned to each NCIS. Table 3 shows this approach. There is no need to point out that choosing the wrong system, a defective installation, or inappropriate handling may greatly reduce the efficiency of the microirrigation project.

To assess the maintenance of the irrigation system, its robustness, its durability, and the need or advisability of checking the emitters at every irrigation event are good indicators. Three levels can be established:

- ○ Low maintenance: Sporadic supervision, very infrequent repairs;
- ○ Medium maintenance: Supervision recommended at every irrigation event, infrequent repairs;
- ○ High maintenance: Supervision at every irrigation event, frequent need for adjustments or repairs.

Buried and robust NCISs do not require maintenance. However, in the case of superficial systems, the more fragile the emitter, the more maintenance is needed. Water recipients can be damaged by animals in search of water. This is why NCISs with tanks must be revised at every refill. The same applies to NCISs with aerial plastic pipes. Should the irrigation water be salty, surveillance must be very strict to avoid the risk of an accidental spill close to the seedling. These general rules make it possible to evaluate the need for maintenance work in each system, as shown in Table 3.

Finally, the methods have been classified by individual or joint usage, depending on whether the emitters have been designed for connection to an irrigation line or not.

Choosing the best alternative will depend on each particular case, including the microclimate, soil, topography, water availability, cost and quality of the water, plant species to be watered, number of years in which watering will be necessary, number of plants to be watered, risk of weed growth, cost of the workforce, simplicity of the management of the system, mechanical means available for watering, aesthetic criteria, landscaping, risk of vandalism, and other factors. An optimal solution suitable for all cases does not exist. The problem has to be analyzed, and a specific solution found for every single case, by assessing the pros and contras of each option and without ruling out conventional irrigation systems beforehand. Moreover, the alternative of not irrigating plants even at the risk of having to replant numerous seedlings that have failed due to water stress must be considered as well [7,96].

5. Conclusions

Irrigation is one of the main tending treatments to be applied in dry zones where afforestation is most difficult. When the risk of seedling failure due to water stress is high, it is strongly advisable to choose a suitable irrigation system in order to avoid costly and recurrent replanting of failed seedlings.

The microirrigation of seedlings differs from traditional agricultural watering both in terms of its aim and the wetting systems it applies. Nonconventional irrigation systems (NCISs) seek the successful establishment of trees and shrubs and not to obtain a harvest or a yield; their discharge equations are different from the well-known conventional equation that depends on gauge pressure.

Currently, a wide range of technological solutions for the microirrigation of seedlings is available, ranging from clay pots to solar distillers, including vertical deep pipes or horizontal perforated pipes, as well as reservoirs with wicks, felts, or other kinds of emitters. Finding the approach that offers the best solution depends on numerous factors that the expert has to consider and weigh up. This paper provides useful data and criteria to make the most suitable choice among the NCISs described in this review.

The NCISs described in this article represent important advancements not only for forestry but also for landscaping, xerogardening, revegetation of road and rail infrastructure, and for arboriculture in arid regions. Although this paper focuses on afforestation, NCISs may also be useful for establishing fruit trees and shrubs in rainfed agriculture (olives, vineyards, palms, almonds, pistachios, carob trees, and others), for truffle cultivation (forest and desert truffles, namely *Tuber* and *Terfezia*, respectively), and for xeriscaping and xerogardening. From an operational point of view, these methods offer a wide range of possibilities, including the possibility to extend the planting period to almost the entire year.

Seedling microirrigation is an emerging sector of the irrigation industry that is rapidly developing and expanding. Two foreseeable future trends can be identified in NCISs—the growing use of permeable plastic materials (whether biodegradable or not) and the connection of single emitters to irrigation lines. Much research still remains to be done on the irrigation systems themselves and their improvement, on the cost of their acquisition, installation, and management, on their water discharge, application efficiency, and their outdoor durability, on the manufacturing materials, and on the repercussions of the development of the seedlings' roots, among many other aspects.

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Appendix A List of Main Symbols

Symbol	Meaning
A	Infiltration surface; surface area of an oozer; cross section of a wick or felt mat (m^2)
AWC	Available water capacity; water retention capacity (mm·m^{-1})
c	Discharge coefficients (unitless)
C_a	Cost of the acquisition and installation of the micro irrigation system (EUR·unit^{-1})
CAP	Pit capacity (L)
D	Irrigation dose (L)
DP	Deep percolation (mm·day^{-1})
e	Thickness of the oozer's walls; wick's length fully saturated with water (m)
E	Evaporation; soil evaporation (mm·day^{-1})
E_a	Water application efficiency (unitless)
E_1	Evaporation from the inner bottle of the Konkom (L·day^{-1})
E_2	Evaporation off the soil inside the Konkom (L·day^{-1})
$ET0$	Potential or reference evapotranspiration (mm·day^{-1})
$F_n(\ldots)$	Function sign (function number n) (unitless)
f	Infiltration capacity (mm·h^{-1})
h	Working pressure head at the emitter (m)
I	Slope of the wick (m/m; unitless)
k	Emitter coefficient (L·h^{-1}·m^{-x})
k_s	Saturated hydraulic conductivity; permeability (mm·h^{-1})
k_{so}	Saturated hydraulic conductivity of the oozer (mm·h^{-1})
k_{ss}	Saturated hydraulic conductivity of the soil (mm·h^{-1})
k_{sw}	Saturated hydraulic conductivity of the wick (mm·h^{-1})Note: Logical inequations to be satisfied: $k_{so} < k_{ss} < k_{sw}$
n	Numerical subscript of the functions (n = 1, 2, 3, ...) (unitless)
Op	Optical properties of the Konkom's outer bottle (light reflection, transmission, and absorption) (W·m^{-2})
P_1	Precipitation by dripping from the ceiling of the Konkom (L·day^{-1})
P_2	Precipitation by dripping from the walls of the Konkom's outer bottle (L·day^{-1})

P_3	Dew on the soil surface of the Konkom (L·day^{-1})
P_4	Occult precipitations inside the soil (L·day^{-1})
q	Emitter flow rate (L·h^{-1} or L·day^{-1})
q_1	Flow rate absorbed by the roots (L·day^{-1})
q_2	Flow rate lost by evaporation (L·day^{-1})
q_3	Flow rate lost by percolation (L·day^{-1})
R_S	Solar radiation (irradiance) received by the Konkom (W·m^{-2})
ST	Soil texture (mm)
T	Air temperature (K)
V_a	Volume of water delivered to the soil by the irrigation system (L)
V_b	Volume of water available for use by the seedlings (L)
x	Emitter exponent (unitless)
X	Characteristic length of the Konkom (m)
Z	Height difference between the porous capsule and the water intake (m)
ψ	Target or characteristic water potential (m)

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