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A Review of Different Types of Lysimeter Used in Solute Transport Studies

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Authors' contributions

All authors contributed equally in this paper. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

A review of common types of lysimeter used in solute transport studies was carried out based on their features, working principle, advantages and disadvantages. The Lysimeters are majorly used for solute concentration measurement at the lower boundary (flux concentrations) in solute transport experiments, and in calculating mass balances for addressing scientific problems and pesticide registration. Lysimeters are commonly used in water flow and solute transport studies in soils. They are known to be of major importance in controlling and measuring water components, chemical concentration and fluxes in soil. Some of the different types of lysimeters reviewed in this paper include; pan or zero-tension lysimeters which are passive water samplers, which looks more like a pan, lacking side walls at the uppermost surface of the pan that can be used to collect draining leachates from the soil. Others are; Capillary wick lysimeter also known as wick sampler is a device used in solute transport studies that is used to sample leachates from soil by gravity through a stationary wick material such as fibre glass or rock wool. Suction cups are the commonest used procedure for collecting leachates from the soil. They are easy to install and gives a masterpiece of experience which makes the procedure unique. Suction plate also known as tension plate lysimeter has a similar working principle like that of porous cup. It is used for different

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extraction plates and also for the entire sampling system. Findings based on this review suggest that the lysimeters reviewed have both advantages and disadvantages. The choice of lysimeter depends on scientific question to be answered by a researcher and the availability of resources for the research. As some of the lysimeters can be constructed using readily available local materials while others involves a rather complex process.

Keywords: Solute transport; lysimeters; soils.

1. INTRODUCTION

A number of contaminants are known to be moving through the soil to the ground. This happen directly through agricultural activities or indirectly from leaking of industrial and municipal wastes disposal sites, or from other activities [1,2]. Recently a large volume of agrochemicals that include fertilizers, pesticides and fumigants are regularly used on agricultural fields, thus making agriculture one of the most important sources for non-point source pollution. This is no different for salts and toxic trace elements which are a result of irrigation in arid and semi-arid regions. Pathogenic microorganisms along with a variety of pharmaceuticals and hormones that are increasingly used in animal production are also polluting the environment through animal waste. Problems with point-source pollution are also not left out, among which are; leaking of underground storage tanks, mine tailings, chemicals spills, nuclear waste repositories, and industrial and municipal waste disposal sites [3]. The degradation of these resources occur which is caused by their movement through soil to the groundwater or discharged to surface water. Mostly, severe human risks are directly connected to this type of pollution. Pesticides, salts, industrial and municipal wastes and nutrients from fertilizers are chemicals of concern. In the case of nitrate leaching, their low productivity is caused by reduction in pH. In the case of nutrients, leaching losses also represent a decline in soil fertility with economic consequences, [4,5]. Owing to the toxicity of pesticides and industrial wastes, even small quantity when present in soil can be transported to the groundwater which can make them persistent for several hundreds of years [6-10].

In order to have an efficient solute transport and leaching studies in the soil, there is a need for accurate and proper methods in the field that will give exact soil solution and drainage water measurement, as well as estimate water fluxes within the vadose zone. The use of lysimeters such as porous ceramic suction cups, zero tension pan lysimeters, gravity drainable soil columns, passive capillary fibre glass wick samplers (PCAPs), and weighing lysimeters and tile drainage samplers are the common and most frequent field methods for drainage water and flux measurement and sampling. This paper is written with the aim of reviewing the different types of lysimeter used in solute transport studies.

2. LYSIMETERS

Lysimeters or soil columns are containers or vessels containing disturbed or undisturbed soils. The optimal surface area and length of a lysimeter depend mainly on the scientific question, the filling procedure, the lower boundary, and the location of installation. The base area is strongly connected to the scale of observation, whereby small-scale heterogeneity will be averaged using large base areas. Lysimeters with crop stands should represent the natural crop inventory and the maximal root penetration depth should be taken into account. They can be filled with either monolithic or disturbed soil or non-reactive materials such as sand. Disturbed lysimeters can be filled with the disturbed horizons of natural soil or artificial material. If disturbed soils or materials are used, the natural texture and the spatial heterogeneity will be changed, which will result in changes of water and solute flow [11,12]. The installation of lysimeters can be in the field [13], at special lysimeter facilities, under controlled conditions in greenhouses, or in laboratories. In the case of installation under natural boundary conditions, the upper surface of the lysimeters should be equal to the ground surface to minimize microclimatic changes. The space between the lysimeter vessel and the surrounding soil should also be minimized to reduce artificial temperature gradients within the soil block. The lower boundary is often segmented to obtain information on the spatial heterogeneity of the water and solute fluxes [14]. For acquisition of the surface run-off, the lysimeters can also be equipped with run-off / overflow tubes [15].

By the drainage behaviour of water from the system, two types of lysimeters can be distinguished: (i) Free drainage lysimeters, where water is allowed to drain freely through the soil under gravity, or (ii) suction controlled drainage system, where a defined suction is imposed at the lower boundary using suction cups, wick samplers, or porous plates.

In general, a free drainage lysimeter is easier to install and cheaper than the controlled suction system. A major concern of the free drainage lysimeter is that the lower boundary is exposed to atmospheric pressure, resulting in an evolution of a water-saturated zone at the bottom of the lysimeter before drainage [16]. This lower boundary imposes temporary anaerobic conditions which may influence degradation, solute transport, and capillary rise during evapotranspiration [17,18]. In comparison, suction lysimeters are more expensive and difficult to install, especially if they have large surface areas. Another problem with suction controlled lysimeters is that water and solutes can interact with the material used for the suction devices. Also, the natural matric potential, water flow streamlines, and the composition of the leachates can be altered. The drainage patterns of both systems have been compared in several laboratory and numerical experiments, with the general finding that suction lysimeters drain more water continuously and in larger quantities [19-21]. A major concern of the lysimeter concept is that it does not account for lateral water and solute fluxes, and that the vertical boundaries may cause fringe effects and preferential flow paths. Several techniques were cited to minimize the fringe effect in lysimeters [22].

The general aim of lysimeter studies is the measurement of solute concentrations at the lower boundary (flux concentrations), in transport studies, and in calculations of mass balances for scientific questions and pesticide registration [23]. If the lysimeter is equipped for volatilization measurements a closed mass balance can be calculated even for volatile substances [24,25]. Additionally, information of the actual evapotranspiration can be drawn if the lysimeter is settled on a scale and if the percolate is logged at short time intervals (e.g., using tipped buckets). Moreover, weighable lysimeters with ground water control are used to measure the soil water balance parameter (example; evapotranspiration, capillary rise and groundwater recharge of sites influenced by groundwater [26].

Lysimeters installed into lysimeter facilities allow additional measurements using hydro geophysical methods [27] such as Electrical Resitivity Tomography (ERT) [28-30] or Ground-penetrating Radar (GPR) [31] for the characterization of the water and solute flow. These techniques may provide additional high spatial and temporal information necessary to describe non uniform transport process within the soil profile. The solutes or leachates collected from lysimeters can be analysed to quantify the extent of transport of solutes such as nutrients in fertilizers, heavy metals from mine tailings, municipal and industrial wastes, sewage and sewage sludge among others. The general features, functionalities, advantages, and disadvantages of the lysimeters reviewed in this study is presented in Table 1.

A wide range of leachates collection efficiencies (Table 2) has been reported in the literature for different lysimeter types. For example, the leachates collection efficiency of the wick-pan lysimeters ranged from 98-108% [32], 66 -80% [33], 125% with a coefficient of variation o f 36% [34], 47-206% [35], and 0 to negligible [36]. Leachates collection efficiency of the zero-tension pans ranged from 10-58% [37].

3. PAN LYSIMETERS

Pan or zero-tension lysimeters are passive water samplers (Fig. 1), typically in the shape of a pan without large side walls extending above the system which will collect freely percolating soil water. The pan lysimeter system itself can be made of different materials such as steel, stainless steel, glass, ceramic, or plastic material depending on the scientific question and the target substance. The sampling surfaces of the system can exhibit several square meters (example, in waste disposal sealing) with standard dimensions being about 0.5 m^2. In general, pan lysimeters are placed below the ground surface to capture drainage water. The installation is comparable to the installation of suction plates. They can also be used at shallow depth, for example, in organic or forest litter layers and hence called humus lysimeters [38,39].

Table 1. The features, functionalities, advantages, and disadvantages of lysimeters reviewed in this study

Type of lysimeter	Features	Functionalities	Advantages	Disadvantages
Pan or zero-tension lysimeters	Shape of a pan, made of materials such as steel, stainless steel, glass, ceramic or plastic	Collect freely percolating soil water, operate reasonably well in soils with large macro-pores near saturation but are much less successful if the soil dries out	Low cost and easy maintenance	Complex installation, that causes considerable disturbance on experimental plots and the divergence of water flow around the system, preventing quantitative estimates of flux concentrations
Wick samplers	Stationary wick material such as fibre glass or rock wool	Water collected from sampling device by placing a water column using wicks; maintaining the lower soil boundary at a pressure lower than the atmospheric, keeping soil unsaturated. Semi qualitative direct analysis of water and solute transport can be achieved by adjusting the properties of the wick-sampler.	Completely sealed system protected from high water tables. Larger sampling volume allows for more accurate analysis.	No overflow port so water must be sampled periodically.
Suction cup	Membranes, ceramic materials and sintered materials	Introduction of a negative pressure by applying suction to cup using a vacuum system. Suction to be applied to porous cup dependent on factors such as the actual amount of leachates required for analysis, actual soil water content, and required time of applied suction.	Easy installation and large treasure knowledge.	Use of independent estimates of soil water fluxes boost the ambiguity of calculated fluxes.
Suction plate	Porous ceramic, nylon membranes, sintered stainless steel and glass	Porous plate inserted into a frame connected to a tube for water extraction. Installed with the aid of trenchor access chamber into an undisturbed soil profile. Hydraulic contact with the surrounding soil should be ensured.	Larger sampling area. Origin of the sampled water and solutes better defined for suction plates than for suction cups because of two-dimensional (2D) surface of the plates, which supports mass balance estimations.	Formation of a saturated zone above the plate resulting in artefacts such as divergent water flow away from the system result in underestimation of the natural water flux.

Table 1 continued….

Resin boxes	Pipe of approximately 10 cm length, with a mesh at its lower end filled with a mixture of quartz sand or silt and an artificial exchange resin	Solute flux estimated following the extraction of these compounds from exchange resins in the laboratory. The resin boxes aimed at estimating solute fluxes through a commonly horizontal defined soil cross sectional area.	Adsorb solutes of percolating soil water reversibly on synthetic exchange resins.	Cannot be use to monitor solute concentrations.

Table 2. Different lysimeters types and their leachates collection efficiencies

Method	Collection efficiencies (%)	Source
Wick-pan lysimeters	98-108	Boll et al. 1991 [32]
Wick-pan lysimeters	68-80	Brandi-Dohrn et al. 1996 [33]
Wick-pan lysimeters	125	Louie et al., 2000 [34]
Wick-pan lysimeters	47-206	Zhu et al. 2002 [35]
Wick-pan lysimeters	0-negligible	Steenhuis et al. 1998 [36]
Zero-tension pans	10-58	Jemison and Fox, 1992 [37]; Zhu et al. 2002 [35]

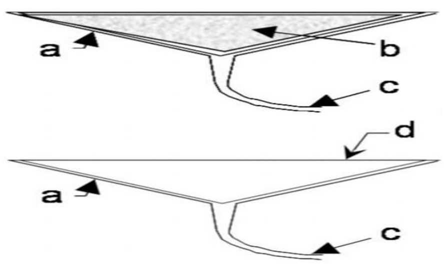

Fig. 1. Schematical sketch of a pan lysimeter and a humus lysimeter with funnel (a), filter body (b) and tube connection (c) Respectively nylon mesh

The installation of the pan lysimeter requires a filling with coarse gravel or some other highly water conductive materials to guarantee easy interception of the drainage water and to divert it to the collection device. Placing gravel in the subsurface soil generally creates a seepage flow boundary condition with a pressure head equal to the atmospheric pressure [40]. Therefore, the soil gets saturated at the interface between the natural soil and the gravel filling. If the pan is filled with coarser material as the ambient soil, a tendency for water bypass is imposed. This occurs as a response of the water potential gradients existing in the soil at the interface and the soil surrounding the system. The amount of bypass flow strongly depends on the water flux rate of flow rate, the textural contrast between the filling material and the surrounding soil, and the gradients in water potential that exist in and around the pan lysimeter.

Due to the design of the sampler and the absence of capillary connection to the soil, pan lysimeters operate reasonably well in soils with large macro-pores near saturation but are much less successful if the soil dries out. Initially, pan lysimeters were used primarily to analyze water quality and only occasionally to quantify drainage rates. More recently, zero-tension lysimeters have been used to estimate drainage rates over a wide range of soil conditions [41-43]. Because of water divergence, collection efficiencies less than 10% have been noted for pan lysimeters. Therefore, diversion around zero-tension lysimeters can be a significant problem. It was also showed that in numerical simulations these seepage face conditions not only influence the water flow, but also the solute concentration in the sampled leachates [44]. The prominent advantages of pan lysimeters are their low cost and easy maintenance. Their major short comings are their complex installation that causes considerable disturbance on experimental plots and the divergence of water flow around the system, which prevents quantitative estimates of flux concentrations and, therefore, complicates the interpretation of solute breakthrough and which may even lead to complete failure of the system. Humus lysimeters show less problems with saturation and bypass flow, due to the fact that humus has a more coarse and open-pored structure.

Humus lysimeters (Fig. 1) only have a nylon mesh at the top and are not filled with gravel or other mineral materials, because the water flowing out of the humus layer should not have contact with mineral surfaces which would cause flocculation and/or changes in solute chemistry [45].

4. WICK SAMPLERS

As the name implies wick samplers or lysimeters (Fig. 2) are devices used in solute transport studies that uses a stationary wick material such as fibre glass to collect soil water by gravity [46] or rock wool [47]. Water is collected from the sampling device by placing a water column using wicks; this maintains the lower soil boundary at a pressure lower than the atmospheric, thus, keeps soil unsaturated. Extent of unsaturation depends on the material, length, and diameter of the wick, the dimension of the sampling bottle, the flux rate, and the soil type [48]. The highest suction to be applied should be between 50 to 60 cm [49].

It was reported that placing an extension tube above the wick can help reduce drainage bypass in wick-type lysimeters [50,51]. This is achieved by filling the extension tube with soil from the excavated hole where the wick sampler will be placed. A semi qualitative direct analysis of water and solute transport can be achieved by adjusting the properties of the wick-sampler [52-54]. Wick samplers have recorded leachates collection efficiencies (LCEs) of equal or more than 100% from lengthy research of previous years. LCEs can be defined as the ratio of measured drainage over the estimated drainage (obtained from a mass balance of precipitation and evapotranspiration). Tipping bucket was integrated into wick sampler in order to have temporal resolution of flux measurements.

No chemical changes on dispersion and retardation were determined by using wick material for most solutes in soil. However, something different was found by another scientist, as his results showed that pH, alkalinity, calcium, magnesium, potassium, aluminium, and silicon concentrations were altered by the fibre glass wick while working with sampled percolate of acid forest soils through weathering of the wick material [55].

It can be concluded that wick lysimeters will give a better understanding of solute transport when compared between the expensive controlled suction plate systems and pan lysimeters which greatly affect soil water flux. Since the wick materials used for the lysimeter construction are manufactured industrially in large scale for heat insulation process, care should however be taken in accessing the variation of their hydraulic and chemical properties which is expected to be high with respect to their use as scientific equipment. This makes testing of hydraulic, chemical and sorptive properties of the samplers a prerequisite during pre-experiments activities. More so, vibrant testing of the samplers before using them in large scale experiments is desirable as the little experience gained using this method cannot guarantee excellent results.

5. SUCTION CUPS

The term suction cup has been described in literature with a variety of names such as porous tube [56], deep pressure vacuum lysimeter [57], vacuum extractor, porous candle, porous cup, or suction cup [58]. The term suction probe can be recommended, since the suction cup or porous cup (as shown in Fig. 3) is only part of the whole system (the small porous body at the lower end) [59]. The term suction cup is adopted for the whole sampling device. The principle of the porous cup was described in the previous years by some scientists and since then they were extensively used in different studies to collect soil leachates for analysis [60].

Several types of suction cups were described by different scientists which are made of diverse materials [61-63]. Generally, they all comprise of cylindrical porous cup which is sealed in a tube. Within the tube, a smaller cup is inserted which is used to collect the leachate. Various materials that range from membranes, ceramic materials and sintered materials are widely used as suction cup materials.

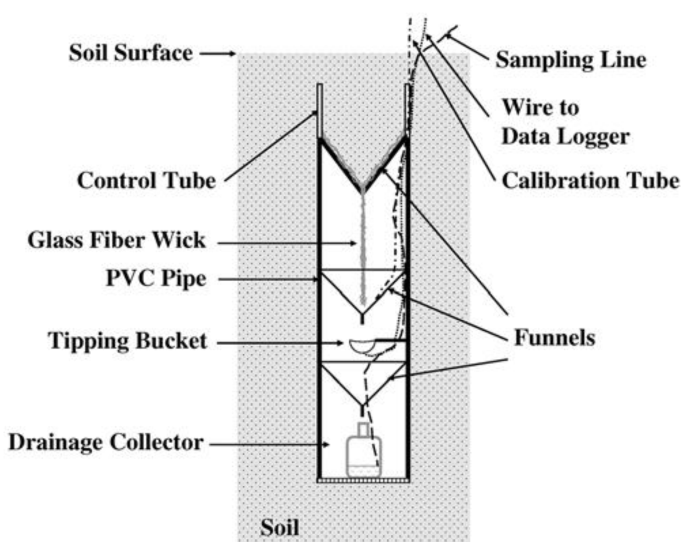

Fig. 2. Passive wick fluxmeter

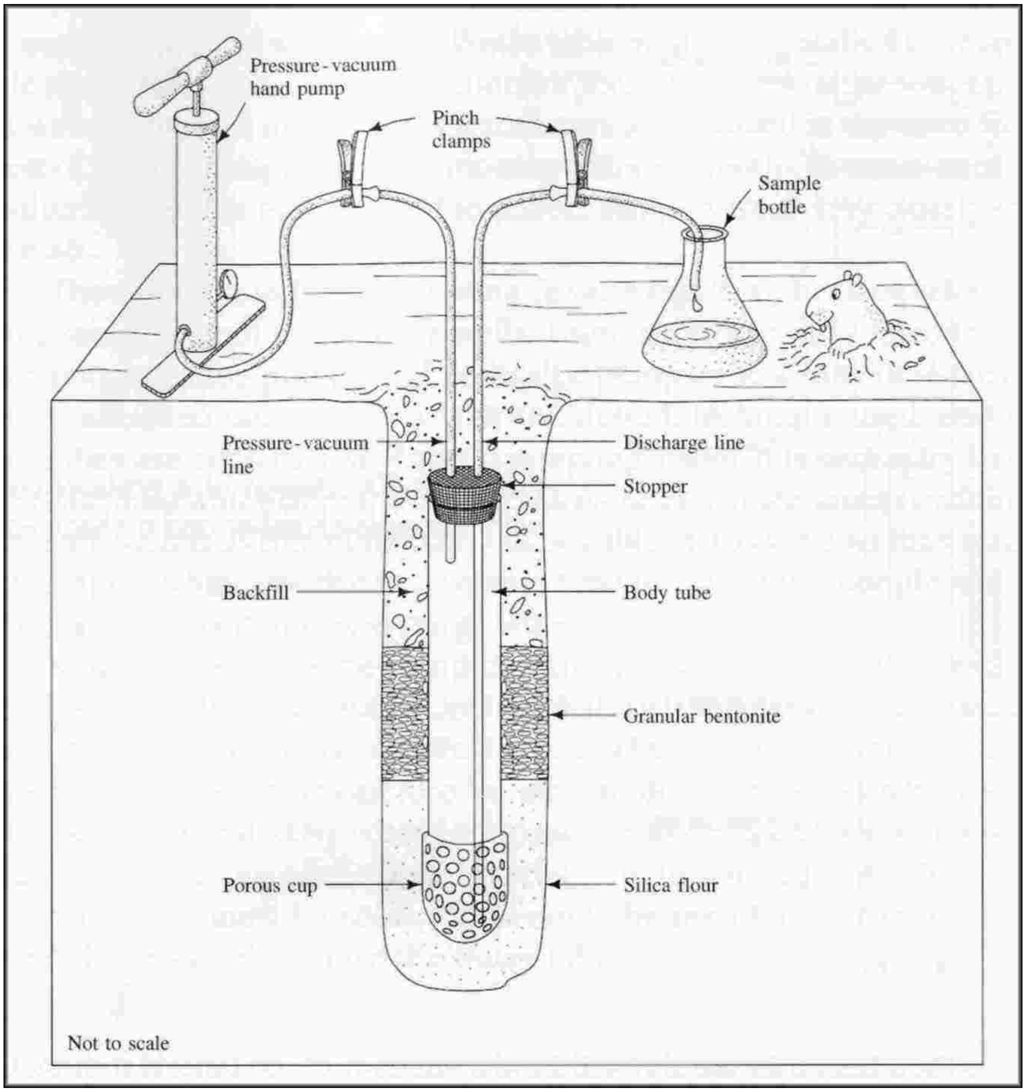

Fig. 3. Schematic sketch of a suction cup

Suction cup installation into the soil profile is straight forward when compared with other water sampling systems. Generally, four installation methods are possible; (i) horizontal, (ii) vertical non-shaft, (iii) vertical and (iv) vertical in 45° [64]. In order to achieve the desired objective, good hydraulic contact between the suction cup and the ambient soil should be ensured especially in stony or coarse sand. This can be achieved by using an aqueous suspension of the fine soil collected from the respective depth or a suspension of quartz silt might be injected into the borehole drilled for installation of the suction cup to ensure good contact.

The working principle of a suction cup involves the introduction of a negative pressure by applying suction to the cup using a vacuum system. The optimal height of applied suction to the cup, and the optimal operation mode are still under debate [65]. Broadly speaking, the suction to be applied to the porous cup is dependent on factors such as the actual amount of leachates required for analysis, the actual soil water content, and the required time of applied suction [66,67].

There are two operation modes for the extraction of leachates from the soil with porous cups:

i. The continuous operation mode involves the application of a potential gradient which depends on the actual pressure head in measuring undisturbed soil using reference tensiometers. Additionally, a predefined pressure off set is added to the measured tensiometer value. The tensiometer controlled continuous operation mode has an edge over other mode in that; it can permanently collect soil water, and consequently a more or less accurate assessment of the drainage pattern [68]. More so, the water withdrawing per unit time will reduce the changes of the natural water flow pattern. Sorption is reduced by the continuous water flow in the cup material and only potential gradients are necessary to collect adequate amounts of water for chemical analysis. The short comings of this method are the potential initialization of preferential flow paths to the cup, a great deal of time needed to preserve the system and high chances of sample contamination during storage under field conditions.

ii. The discontinuous operation mode involves collecting water during selected short-time intervals. Presence of solutes at specific points of time is indicated by this mode of operation [69]. Small temporary disturbance of the natural flow and ease of maintenance are the major advantages of this operation mode. While the short coming is the non-permanent flow through the cup material, which can result in high sorption. This makes discharging the first water desirable. Short time events which cause rapidly changing concentrations of solutes by heavy down pour and preferential flow are not adequately recorded which makes it the leading short coming of this method [70].

The most common method of soil water extraction method is the use of suction cups. Their easy installation and large treasure of knowledge are the most important advantages of this method. Moreover, the necessity to use independent estimates of soil water fluxes boost the ambiguity of calculated fluxes. Other methods, which aim at preventing these restrictions, have been proposed since the early beginnings of in situ soil water extraction [71].

6. SUCTION PLATE

Suction plates uses a terminology similar to that of suction of cup. The term suction plate or tension plate lysimeter as shown in Fig. 4 is a water sampling device that is used for separate porous extraction plates and also for the sampling device. In a broad spectrum, the porous pate is inserted into a frame connected to a tube for water extraction. The available materials for the porous body are porous ceramic, nylon membranes, sintered stainless steel and glass. Porous plate is installed with the aid of trenchor access chamber into an undisturbed soil profile. Care should be taken to make sure there is hydraulic contact with the surrounding soil.

A number of control options have been proposed for the applied tension. Zero tension has been identified as the simplest operation method, which involve no application of suction to the device. Formation of a saturated zone above the plate resulting in artefacts such as divergent water flow away from the system which result in underestimation of the natural water flux is recognised as the major short coming of this operation method. In numerical simulations these seepage face conditions not only influence the water flow but also the solute concentration in the sampled leachates.

The second operation mode involves the use of fixed predefined function which is applied to the plate. There is variation in matric potential of the soil which is a function of time and space. This causes the soil water regime in surrounding area of the plate to be different from fixed suction exerted by the plates. These results in changes of the natural flow field, and therefore, in differences in the solute concentration compared to the freely percolating water in the soil profile [72,73].

The best approach is used to overcome this limitation in order to sample soil water with porous plates which involve the application of suction equal to the ambient matric potential at similar depth [74-76]. Reference tensiometers are used in measuring the ambient matric potential and routinely applied to the plates.

This control strategy is expected to sample representative water flow and solute concentrations with little disturbance of the natural flow field. Nonetheless, the solute concentrations and calculated solute transport parameters from solute breakthrough curves sampled with suction plates should be verified using water balance models, water tracers, or numerical simulations [77].

In contrast to suction cups, porous plates possess a larger sampling area. The plate arrays make the detection of preferential flow events

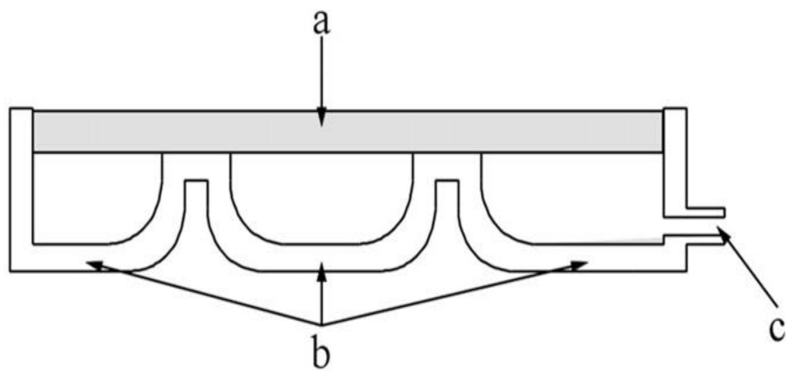

Fig. 4. Schematic sketch of a suction plate with porous body (a), frame (b), and tube connection (c)

possible [78]. The origin of the sampled water and solutes is better defined for suction plates than for suction cups because of the two-dimensional (2D) surface of the plates, which supports mass balance estimations. However, these advantages are connected with larger efforts and disturbance of experimental plots for installation as compared to the installation of suction cups.

7. RESIN BOXES

Resin boxes (Fig. 5) have the ability to adsorb solutes of percolating soil water reversibly on synthetic exchange resins. Solute flux is estimated following the extraction of these compounds from the exchange resins in the laboratory. The resin boxes are aimed at estimating solute fluxes through a commonly horizontal defined soil cross sectional area. Monitoring of solute concentrations cannot be done with this method. The resin box consist of a pipe of approximately 10 cm length, which is provided with a mesh at its lower end and filled with a mixture of quartz sand or silt and an artificial exchange resin [79,80]. The type of exchange resin depends on the compound in question. In the case of organic compounds, strong cation and anion exchange resins but also less polar sorbents can be used.

Passive diffusion of solutes can be minimized by placing layers of exchange resins at the top and at the bottom of the boxes [81]. Biological transformation is a condition for the stabilization of adsorbed compounds for extended monitoring periods [82]. A variation in flow field of soil-water from natural conditions around the box is likely to occur owing to the hydraulic properties of the resin boxes that deviate from those of the surrounding soil. Tracer experiments can help characterize the extent of probable bias of estimated solute fluxes that is induced by perturbation of flow field [83].

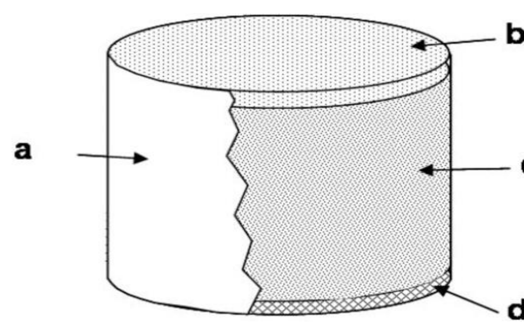

Fig. 5. Exemplary sectional drawing of a resin box. Pipe (a), filling of quartz sand or silt (b), mixture of quartz sand or silt and exchange resin (c), mesh (d)

8. CONCLUSION

The lysimeters presented provides an alternative method for collecting agrochemical leachates in solute transport studies. These devices can be used to compare best management practices, identify and quantify potential pollutant sources, and gain a better understanding of the infiltration properties of a particular soil type.

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COMPETING INTERESTS

Authors have declared that no competing interest exists.

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