Aspects to consider for optimizing a substrate culture system with drainage recycling

Aspectos a tener en cuenta para optimizar un sistema de cultivo en sustrato con reciclaje de drenajes

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ABSTRACT

In Colombia, the soilless system have been implemented in the cut flowers industry, among others, due to soil limitations. The use of substrates as growing media requires drain around 30% of the applied fertigation solution to avoid the rhizosphere salinization. The drainage solution is spilled out to the soil and it reaches the water table, producing environmental hazards; although the drainage solution could be recycled or reuse, depending upon their chemical characteristics. The nutrient up takes by the plants depends upon their phenological stage and the nutrient concentration in the solution; which could be lead to ion depletion or accumulation. In general, monovalent ions are withdrawn faster than divalent ones. An efficient drainage treatment involves the automated sensing, evaluation of ion concentration and recycling. The system should take into account chemical aspects in the recycled and the new solutions in order to predict the life time of the drainage solution from EC and pH. The system must be integrated with disinfection methods to avoid the spreading of plant pathogens. This review point out the physiological and technical bases, that should be considered in a drainage recycling system in established crops under substrates, as a tool to take decisions more efficiently.

Key words: leaching, pollution, automation and control, soilless cultivation, ion imbalance.

RESUMEN

En Colombia, el sistema de cultivo sin suelo es una práctica común en los cultivos de flores de corte, debido entre otras causas, a las limitaciones de algunos suelos para la producción. Utilizar sustratos como medio de crecimiento implica generar como drenaje aproximadamente el 30% del total del fertirriego aplicado, para evitar la salinización de la rizosfera. Comúnmente estos drenajes son vertidos al suelo con los consecuentes problemas de contaminación, aunque sus características químicas son apropiadas para ser recirculados o reutilizados. La absorción de nutrientes por la planta depende del estadio fenológico y de la concentración de iones en la solución; lo que puede llevar al agotamiento o acumulación de iones. De forma general, los iones monovalentes son removidos más rápido de la solución que los divalentes. Un reciclaje eficiente requiere captar, evaluar y reciclar la solución automáticamente; para lo cual es necesario considerar aspectos químicos de las soluciones nueva y reciclada, para estimar la vida útil de la solución drenada a partir de CE y pH. Así mismo, integrar métodos de desinfección para evitar la dispersión de patógenos. Esta revisión presenta las bases técnicas, avances tecnológicos y fundamentos fisiológicos que enmarcan y definen las características de un sistema de reciclaje de drenajes en cultivos establecidos en sustratos, como herramienta en la toma de decisiones de manera eficiente.

Palabras clave: lixiviados, contaminación, automatización y control, cultivo sin suelo, desbalance iónico.

Introduction

To counter the rising costs of production decurrent increased use of protected agriculture increased use of protected agriculture, farmers have been increasing productivity using different technological advances, including the use of substrates (Raviv and Lieth, 2008). One reason that justifies the change from soil culture to substrate cultivation is the proliferation of diseases, as in the case of vascular wilt in cut carnations in Colombia (Pizano Marquez, 2001), in which, to control the causative agent (*Fusarium oxysporum* f.sp. *dianthi*), expensive fumigant applications were used (Patiño, 2000). Another factor is better control of fertilizer solution variables, such as pH, electric conductivity (EC) and concentration of ions, improving productivity (Olympios, 1999).

The tendency to intensify agriculture for increased productivity is accompanied by increased use of fertilizers, particularly inorganic nitrogen. Use of this component peaked at 11 million t annually in the mid-1980s and recently dropped to about 9 to 10 million t (European Commission, 2000).

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In the Netherlands, the law requires, since 2000, the use of closed systems or recycling of the nutrient solution in 100% of cultivated areas to mitigate pollution, particularly of surface waters (Van Os, 1999). In Mediterranean countries, the law states that the leachates from soilless culture systems (SCS) should be treated as industrial discharge; and that for crops grown in nitrate vulnerable zones, one must apply irrigation scheduling methods that allow maximum water use efficiency (Marfà *et al*., 2000).

In carnation production with open substrate culture systems, it is estimated that 4,200,000 m^3 $year^{-1}$ of water and 2,000 t $year^{-1}$ of salt fertilizers are disposed of, based on a 30 to 40% drainage percentage (van Kooten *et al*., 2004). Dumping legislation in Colombia (Vélez, 2010) puts forth that in the diagnostic phase, one shall identify and characterize the problems caused by imbalances in the natural environment, the degradation in quality or quantity of renewable natural resources, natural and man-made hazards, environmental impacts, among others. The regulation seeks to establish the parameters and maximum permissible values for discharge to surface waters and groundwater, refers to product dumping for activities such as growing cut flowers and sets maximum allowable limits for many of the common effluent substances in agroindustrial processes (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2011).

The aim of this review is to present the technical basis, technological advances and physiological fundamentals that frame the characteristics of a recycling drainage system in substrate cultivation, with the purpose of presenting a tool for the efficient use of resources in horticultural production.

Soilless culture

With a disposal of 2,000 m^3 ha^{-1} of water (with 20% sewage) and fertilizer losses of up to 5 t ha^{-1} in the Netherlands and Belgium (Marins *et al*., 1998), they have implemented rules forcing producers to recycle drained solutions. In the Netherlands, the discharge of nutrient solution is allowed only if the sodium in the drainage solution is between 3 and 8 mm, depending on the crop species, with drainage of sodium concentrations greater than 4 mM for roses and 8 mM for tomatoes (Baas and Berg, 1999).

Implementing a SCS leads to a more rational use of water, fertilizers and pesticides, and reduces pollution and production costs (Gent and Short, 2012). In a tomato crop with automatic recycling, water savings rates for fertigation (31.5), phosphorus (31.4), nitrogen (29.9), potassium (29.8) and calcium (28.2) were achieved (Dhakal *et al*., 2005).

According to Martinez and Morard (1999), by implementing the SCS with appropriate recycling of the nutrient solution, one can achieve savings of up to 30 and 50% for water and fertilizers, respectively. While Richard *et al*. (2001), in a rose cultivation system using low-tech drainage recycling based on control of the EC, obtained savings of 42% in water and 55% in nutrients, without affecting the quality of the flowers. Experimentally closed SCS in Mediterranean conditions can produce excellent quality carnation flowers using water with average chemical characteristics, with low concentrations of sodium and chlorine, maximizing efficient use of water and nutrients. The recycling system and disinfection of the solution did not require great technical skills, but weekly analysis of the solution and leachate is needed for proper management (Marfà, 1999).

The yield of plants in SCS is higher in comparison with the traditional soil system, which makes this cultivation technique of interest for increasing the food supply (Raziq, 2007).

Substrate culture systems use organic or inorganic substrates to replace the soil as the anchor and media of providing nutrients to the plants. The physical, chemical and microbiological properties of the substrates are essential, because, due to the reaction with the nutrient solution in the root environment, characteristics vary over time and may affect the availability of nutrients and water retention (Martínez and Roca, 2011). A growth media that has a proper balance between water availability and aeration of the roots will optimize the yield and quality of horticultural crops (Casadesus *et al*., 2007).

For proper management of irrigation and fertilization, it is important to understand the factors affecting the availability of air and water in a substrate. The water retention curve (WRC) establishes the relationship between the matric potential and volumetric water content and is used to estimate the availability of water and air in substrates (Wallach, 2008). In addition, the WRC derives the container capacity, the pore space occupied by air and water, and the water that is readily and not readily available for the plant (Murray *et al*., 2004). The importance of these soil hydraulic functions and their difference with values obtained for mineral soils are described by González *et al*. (2006a) and the effect of the variation of these features on the substrate, by González *et al*. (2006b).

In Colombia, since 1992, cultivation substrates in open systems have been used for the production of cut flowers. Previously, SCS was used to produce hydroponic vegetables and forage. The most widely used substrate for growing flowers has been burnt rice husk (BRH), initially not burnt; later, fermentation and aging were employed in order to improve the water retention capacity (Calderón and Cevallos, 2001). The husk mixture with other materials such as coal slag, river sand and husk ash has also been used to improve moisture retention.

The BRH, with a higher quantity of fine particles, has a high water holding capacity, while coconut fiber (CF) has larger particles and lower retention. In the studied substrate mixtures, there was a reduction in the rate of decomposition and washing of BRH; and the variations in volume of air and the amount of readily available water aided the definition of the appropriate conditions in water management for production (Quintero *et al*., 2009).

Recycling drainage

One way to counter the environmental pollution generated by the SCSis the use of leachate recycling techniques, which take advantage of the fertilizing potential. This is achieved by implementing a suitable system for drainage isolation and subsequent treatment for recycling the saline solution (Gent and Short, 2012).

The success of closed SCS depend on knowledge and management of the nutrient solution. Most of the water used for irrigation has high concentrations of salts, especially sodium and chloride, elements that are poorly absorbed by most plants, which can affect the reduced volume of roots, characteristic of SCS (Sonneveld and Van der Burg, 1991). This accumulation can be prevented by washing with additional water applications, which also leads to considerable losses of nutrients (Sonneveld, 2000).

The salts that are not absorbed by the crop are drained and tend to accumulate in the recirculating nutrient solution, therefore it must be leached (removed from the system) frequently, particularly under high temperature environments where salt accumulation can reach 2 dS m^{-1} (Incrocci *et al*., 2006).

Maas and Hoffman (1977) modeled salt tolerance with the following characteristics: (1) salinity threshold value (STV), which is the maximum value of salinity which does not present a significant reduction in growth or yield and (2) the salinity yield decrease (SYD), a value that indicates the percentage of decrease in yield per unit increase in EC over STV.

Sonneveld *et al.* (1999) concluded that the sodium and chloride absorption by a plant increase with increasing concentrations in the root environment, and so it would be an advantage to counteract their accumulation in the rhizosphere, however, this depends on the species. For the carnation the values have been calculated as: STV of 4.3 dS m^{-1} and SYD of 3.9% per dS m^{-1}; and for the rose: STV of 2.1 dS m^{-1} and SYD of 5.3% per dS m^{-1}. Low EC values can produce inadequate input elements and nutritional deficiencies (Graves, 1983). In contrast, EC values over the STV decrease performance due mainly to osmotic effects which are influenced by the composition of the nutrient solution (Savvas, 2003). Salinity affects the quality of cut flowers, decreasing the length and diameter of the stem, firmness and vase life (De Kreij and Van Den Berg, 1990). In the case of gerberas and roses, these species respond by reducing the number of flowers more than the average weight of the flower, while in carnations and bouvardias the opposite occurs (Sonneveld *et al*., 1999).

In some growers of cut the flowers in the Bogotá Plateau, leachates are channeled to the water supply reservoir, and then the irrigation water is used in the preparation of a new fertigation solution. This is not considered proper recycling since the chemical composition of the reservoir water is altered with ions poorly absorbed by plants. It is necessary to develop techniques of recycling that isolate drainage solutions for recomposition.

In this context, a culture system based on the reuse of the leached solution or recycling of the drainage solution would contribute to the optimization of the SCS technique in protected agriculture. Cleaner production techniques benefits the marketing of products since this production system involves the use of good agricultural practices, which is certifiable by green labels. By adopting this technique, the discharge of water and fertilizer salts will be reduced, especially of nitrate, phosphorus and potassium, mitigating environmental impact, reducing costs and preserving water sources (Sengupta and Banerjee, 2012).

Basic concepts

Among the most important variables to consider in SCS are: the rhizosphere temperature, pH of the solution, concentrations and ratios of nitrate and ammonium, container size or root volume, growth media, EC and root aeration (Kafkafi, 2001). Besides EC and pH in the preparation of the initial solution, the concentration ratios of nutrients and water quality must be taken into account (Savvas and Adamidis, 1999).

The following define some important concepts for managing closed SCS (Stanghellini and Kempkes, 2002). They are variables that depend on the type of substrate, the weather and the phenological state of the plant; and they are important for determining the water relations and balances over time.

Volume of water used (V_U): volume that is used to restore the system volume, equals the volume of the new nutrient solution; irrigation volume (V_I): volume of solution applied to the crop in a time interval; pulse volume (V_P): volume of solution applied in an irrigation event; volume absorbed (V_A): The amount of water used by the crop at a particular time and is equal to the transpiration and growth in biomass increase, which is usually less than the 10% of the transpiration; drained volume (V_D): amount of water flowing out of the root zone; leachate volume (V_L): amount of water leaving the system; leaching fraction ($LF \equiv V_L / V_U$): ratio between the volume exiting the system and the volume of water used in a given period; leaching requirement ($LR \equiv V_L / V_A$): ratio between the volume exiting the system and the volume of water absorbed by the plant, in a given period, Operational EC (EC_O): average of the EC desired for the system, leachate EC (EC_L): EC at which the system solution should be discarded.

Variations in pH

The pH in the root zone for most hydroponics is between 5.5 to 6.0. Values between 5.0 to 5.5 and from 6.5 to 7.0 would not cause problems in most crops (Graves, 1983), while values greater than 7.0 may cause problems in the absorption of P, Fe and Mn; and sometimes deficiency symptoms for Cu and Zn (de Rijck and Schrevens, 1997).

The pH values in a substrate system have large variations during the growing season, partly due to small volume, especially when the substrate used has a low buffering capacity. However, pH variations are greater in inert substrates, and more stable in organic substrates. The buffering capacity of the nutrient solution used is very low and almost only determined by the phosphorus concentrations (Sonneveld, 2002).

Vélez (2012) evaluated recirculation rates and substrates based on BRH and CF in culture system for carnation, and found that the pH in the leachates tended to decrease and in the substrates, was constant during the study period but increased with an increase in percentage of BRH.

In periods of high growth rate and with sufficient light intensity, anion absorption normally exceeds cation absorption, which is due to high absorption of nitrate and its use in plant metabolism. This difference in rate of absorption of ions is compensated by the release of HCO^{3-} and OH^- to rhizosphere (Ben-Zioni *et al.*, 1971), increasing the pH of the root zone. However, under conditions of low light intensity, this situation is reversed, thus reducing the use of nitrate and increasing the cation:anion absorption ratio; rapid uptake of cations is compensated by the release of H^+ by the roots (Graves, 1983).

The pH in the solution can be controlled by: (*i*) modification of the NH_4:NO_3 ratio in the recycled solution and (*ii*) application of the required nitrogen in nitrate form and reducing the pH with acid. By not adding acid, the first method reduces the salt load in the system, however, ammonium may inhibit absorption of Ca, Mg and K and impair the development of the roots at high substrate and solution temperatures (Bar-Yosef, 2008).

Physiological considerations - Concentration of elements in the solution

The composition of the nutrient solution is defined by the known total salt concentration, pH, concentrations of micronutrients, and ratios between the macronutrients and the irrigation water composition (Savvas and Adamidis, 1999).

It has been established that the absorption of nutrients by the plant is specific for each solute and follows the Michaelis-Menten dynamic (Claassen and Barber, 1974). In this respect, based on the rate of absorption of the solution, Bugbee (2003) placed essential nutrients into three categories (Tab. 1), wherein the monovalent ions are more efficient (Schippers, 1980). However, the ion uptake mechanisms are different for each ion and each species of plant and therefore the passive and active absorption terms should not be taken literally as plant chemistry plays an important role (Marschner, 1995) through the stoichiometry of some elements (Ågren, 2008). One drawback in individual ion monitoring is the concentrations of the elements N, P, K, and Mn, which should be kept low to prevent toxic accumulation in plant tissues. The total amount of the nutrient solution can be determined easily and with some precision from the EC of the solution. However, because of the differential removal rate through the absorption of nutrients, EC mostly measures the concentration of calcium, magnesium and sulfate remaining in the solution. Micronutrients contribute less than 0.1% to the EC (Bugbee, 2004).

TABLE 1. Classification of elements in the nutrient solution according to their rate of absorption.

Removal rate	Elements
Active absorption, quick removal	NO_3, NH_4, P, K, Mn
Intermediate absorption	Mg, S, Fe, Zn, Cu, Mo, Cl
Passive absorption, slow removal	Ca, B

Source: Bugbee (2004).

When irrigation water is poor in quality there is a rapid increase in EC due to the accumulation of sodium, chloride and sulfate, and, in the case of hard water, calcium and magnesium. The bicarbonates commonly present in groundwater are neutralized with acid. On the other hand, micronutrients such as boron or heavy metals may accumulate to toxic levels, even though their concentrations are in the order of micromoles per liter; unlike other ions that are determined indirectly by measuring the EC, these have to be monitored by costly laboratory analysis (Olympios, 1999; Carmassi *et al*., 2003).

One reason for the rapid buildup of chloride is its weak retention in soil and subsequent leaching due to high mobility (Marschner, 1995). It is an essential element for all plants and its addition may be a strategy to reduce nitrate levels in accumulator crops, due to the antagonistic effects between these two ions (Chapagain *et al*., 2003).

According to Savvas (2003), in the case of actively absorbed macronutrients such as N, P and K, maintaining low concentrations could obtain good yields; with the best results when the concentrations of elements in solution correspond roughly to the ratio of nutrient absorption: water (Sonneveld, 1981; Graves, 1983). Under these conditions, plants do not consume energy to actively take or exclude ions (Steiner, 1980), however, the nutrient absorption:water ratio fluctuates in response to climatic conditions, which makes the preparation of a solution that has a consistent ratio difficult (Savvas, 2003).

The excess of nitrate in the restitution solution increases dry mass allocation in the leaves at the expense of shoots and inflorescences. pH values between 3 and 4 increase the absorption of P, and its concentration in leaves, reducing the biosynthesis of sucrose and adversely affecting the yield of flowers. For Bar-Yosef *et al.* (2009), using appropriate mixtures of NO_3, NH_4 and urea reduced the harmful effects caused by changes in pH, which cause ionic imbalances and competition for absorption of Ca, P, Mn, and other elements.

In practice, in systems based on organic substrates, it is difficult to track the variation in the concentration of micro elements (Cu, Fe, Mn, Zn and B), possibly due to changes in physical, chemical and microbiological properties of the substrates. In carnations, in a systems established in BRH and CF based substrates, with three recycling rates of the drained solution, Mesa *et al.* (2011) reported increases in EC and Cu concentration along with a trend of pH reduction during the transition between vegetative and reproductive stages. With the same system (Vélez *et al*., 2012), the nitrate concentration in the leachate was influenced by levels of recirculation and for the substrates factor decreased as the BRH content increased. For phosphate, the concentration in the leachate was influenced by the BRH percentage. While the potassium concentration in the leachate tended to increase with age of the plant after the "transition" stage; only influenced by the substrates, with significantly higher concentrations in treatments with higher BRH contents.

In a hydroponic system, the lowest nutrient absorption occurred when rose flower stems reached the maximum elongation rates; with the reduction in the growth rate increased nutrient uptake, nutrient uptake increased, reaching a maximum when the stems were ready for harvest. This contrasts with the common belief that the absorption rate is linked to the phenological development of rose flower stems (Cabrera and Solís, 2009).

The temperature and oxygen concentration of the solution also require control. For example, in the production of *Brassica chinensis* L. in the nutrient film technique system (NFT), a 10°C increase in ambient temperature (25 to 35°C) decreased the percentage of dissolved oxygen from 80 to 30% (Kao, 2002). In a nutrient solution which contains ammonium and nitrate, the absorption of ammonium is favored when the temperature in the root zone is low, between 3 and 11°C (Clarkson *et al*., 1986). For Rouphael *et al.* (2008), during the winter season, the solution fertigation concentration may be reduced about 50% without adversely affecting the plant. The association of the growth index as a function of efficient water use and the parameters solar radiation, average air temperature and vapor pressure deficit are considered tools for reestablishing fertilizer formulas.

Quantitative information is needed from the absorption of water and ions during crop development. Besides essential ions, considering the absorption of other ions such as sodium and chloride is necessary to avoid accumulation in the root environment. Ratios and the amounts of nutrients absorbed vary with the stage and conditions of the plant development. Unanticipated changes in the composition of the nutrient solution frequently occur in commercial systems, and it is necessary to analize the root environment (Sonneveld, 2000). Similarly, the composition and volume of the drained nutrient solution will vary over time and will be affected by the number of cycles of reuse.

The correction procedure of the nutrient solution can be performed in two ways: by conventional control based on the adjustment of the EC or programmed addition of nutrients. Kläring (2001) provided three ways to control these supplies: adding water and nutrient amounts that are expected to be taken by the plant, control of water content and concentration of nutrients in the root zone as well as and in the tissues. One of the prerequisites for the proper replenishment of drained solution is the addition of nutrients in an appropriate ratio (Savvas and Gizas, 2002).

For Van Noordwijk (1990), it was critical to synchronize demand and supply of nutrients to increase use efficiency. One tool is the mathematical modeling in controlled conditions. Models of nutrient uptake have been proposed, such as, Barber - Cushman model (Cushman, 1979; Barber, 1995), the mobile limit (Reginato *et al*., 2000) and one that considers the increase in root density and competition between them (Hoffland *et al*., 1990). Carmassi *et al*. (2005) developed a model for the tomato crop to predict changes in ion concentration and the EC of the recycled solution. It was designed based on a balanced nutrient absorption equation and simulates the accumulation of salts in the solution when prepared with low quality water, in order to program the times for solution disposal.

Silberbush *et al*. (2005) proposed a model of water and nutrient flow, and their uptake by the plant. It takes into account the loss of water through transpiration and the accumulation of salts in the solution, including the interaction of this effect with the absorption of water and nutrients. By developing a similar model and integrating it with a computer-aided control, one can automate the management of a closed SCS.

Gieling *et al*. (1997) proposed controlling closed SCS by maintaining the flow rate and concentration of the drained solution at a fixed point. This concept has the ability to compensate for changes in the absorption of water. If absorption by the plant decreases, the drained volume will be increased, thereby compensating with a low volume.

Pathogen control

Presumably one of the common problems in drainage recycling systems is the spread of pathogens in the liquid medium, since the reapplication of a contaminated solution facilitates their dispersal throughout the crop (Poncet *et al*., 2001). Passive disinfection techniques such as slow sand filtration, leave part of the resident microflora alive, while active methods such as UV, pasteurization and chemical use control harmful and beneficial organisms. The use of microbiological methods is environmentally friendly, microorganisms are active throughout the system, but more knowledge is needed about the whole process in the growth media and nutrient solution (van Os and Alsanius, 2004).

Ozonation, thermal and UV disinfection methods require a large investment and therefore are used when production justifies the cost; furthermore, they must be used in conjunction with sand filters to increase effectiveness (Ehret *et al*., 2001; Barth, 1999).

The effectiveness of slow flow sand filter (SSF) has been verified at different latitudes (Hoitink and Krause, 1999) as an appropriate method for the control of microorganisms present in the solution; it is a low cost system whose action lies in natural control exercised physically and biologically (Calvo-Bado *et al*., 2003). Koohakan *et al*. (2004) found that cropping systems such as NFT and DFT (Deep Flow Technique) contained high amounts of *Pythium* sp. compared with substrate systems. The NFT contained the largest population of *Fusarium* sp. when compared to other SCS.

One of the risks of using chemicals for disinfecting nutrient solutions is chemical residue in the leached solution. The use of compounds with chlorine is not justified due to the environmental and health risks. UV disinfection and SSF appear to allow for a chemical-free management of the recycled solution. Garibaldi *et al*. (2004) concluded that among the best controls for the incidence of *Phytophthora cryptogea* in gerbera cv. Goldie cultivated in a recycling system were SSF filter and UV radiation system.

It has been found that the proliferation of strains of *Pseudomonas fluorescens* colonizing roots has controlled pathogens such as *Sclerotinia sclerotiorum* (Li *et al*., 2011) and *Fusarium oxysporum* f.sp. *Radicis-lycopersici* (M'pinga *et al*., 1997).

Furthermore, the substances exuded by the roots of the plants could become a major problem in closed hydroponic systems. Temperature and photoperiod are related to the quality and quantity of root exudates, and these compounds can inhibit the growth of roots and produce autotoxicity (Pramanik *et al.*, 2000).

Conclusions

Local research results show the need for farmers to know the hydrophysical characteristics of the substrate as well as the interaction of nutrients with the drained solution and the substrate itself in order to improve fertigation application processes.

It is necessary to establish guidelines for the design, monitoring and control of SCS according to their minimum components: substrate, plant, nutrient solution and environment. Understanding the variations in the physical, chemical and biological characteristics, framed within the environmental and sustainability standards, will make it possible to implement controlled systems.

Studies must address the system components in order to: define the physical, chemical and biological characteristics for setting up an appropriate substrate; understand the dynamics of recycled nutrient solutions and thereby control the useful life of the drainage without affecting yields; and determine the influence of the components on the productivity of cultivated plants.

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