GUILLAUME LÉTOURNEAU

MOUVEMENTS DE SELS EN SUBSTRATS ORGANIQUES POUR LA CULTURE DE LA TOMATE DE SERRE

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DÉPARTEMENT DES SOLS ET GÉNIE AGROALIMENTAIRE
FACULTÉ DES SCIENCES DE L'AGRICULTURE ET DE L'ALIMENTATION
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RÉSUMÉ

L'utilisation de substrats composés de sous produits peut être envisagée par les producteurs serricoles pour diminuer leurs impacts environnementaux et favoriser un développement durable de l'industrie. Pour la culture de la tomate, des mélanges de sciures et de tourbe ont démontré leur potentiel, mais ces substrats sont sujets à une accumulation problématique de sels en cours de culture. Cette étude vise l'obtention d'une meilleure compréhension des phénomènes liés aux mouvements de sels dans les substrats de culture. Un essai de culture en serre de la tomate a été réalisé pour effectuer un suivi de la salinité dans différents substrats et des expériences de lessivage en laboratoire ont été faits pour déterminer la proportion d'eau immobile qu'ils contiennent. Sans que les rendements n'en soient affectés, des salinités élevées et une proportion d'eau immobile importante liée à la présence de substances humiques ont été observées dans des mélanges de sciures et tourbe.

ABSTRACT

The use of growing media composed of byproducts can be considered by greenhouse producers in order to diminish their environmental impacts and achieve sustainability. For tomato production, peat and sawdust mixtures have shown great potential, but these substrates are subject to a problematic salt accumulation during production. This study aims at a better understanding of the mechanisms controlling salt movements in these growing media. A long term greenhouse experiment was realized in order to monitor the evolution of salinity in different substrates during tomato production, and laboratory leaching experiments were conducted to investigate the presence of an immobile water phase in the same substrates. Important salt accumulation during tomato production was observed in peat-sawdust mixtures, but yields were not affected. An important immobile water phase was also observed in these media, it was suggested to be controlled by the presence of humic substances.

AVANT-PROPOS

Ce mémoire de maîtrise est constitué de quatre chapitres. Après une description de la problématique associée à ces travaux au chapitre 1, les chapitres 2 et 3 sont présentés sous forme d'articles scientifiques rédigés en anglais dont je suis l'auteur principal et qui seront éventuellement soumis au magasine *Vadose Zone Journal*. Le chapitre 4 regroupe ensuite les principales conclusions des deux articles et les replace dans le contexte de la problématique.

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INTRODUCTION

L'industrie de la culture en serre est un secteur dynamique qui revêt au Canada une grande importance, générant annuellement des revenus évalués à deux milliards de dollars. La culture légumière compte pour le tiers de ces revenus et le produit le plus rentable est sans contredit la tomate (*Lycopersicon esculentum*) dont la vente représente plus de la moitié des revenus du secteur légumier (Statistiques Canada, 2007). Le Québec joue à ce titre un rôle important, regroupant en son territoire 12% de la superficie canadienne dédiée à la culture de serre (Statistique Canada, 2007).

Faisant face à une concurrence féroce des industries américaines et mexicaines, les producteurs canadiens se doivent, afin de demeurer compétitifs, d'améliorer continuellement leur productivité tout en fournissant des produits de qualité supérieure. De 1998 à 2003, les rendements des plants de tomate ont d'ailleurs augmenté jusqu'à 27% suite à l'introduction de nouvelles technologies et méthodes de production (Statistique Canada, 2007). En plus de l'amélioration du contrôle climatique et du développement de cultivars plus performants, le passage vers une régie de culture de type hors-sol a fortement contribué à cette augmentation de rendement.

Au Canada, 95% de la culture en serre de la tomate est réalisée en culture hydroponique sur des milieux de culture artificiels (Lemay, 2006). Les plus utilisés sont actuellement la laine de roche et la fibre de coco. Ces substrats possèdent de nombreuses propriétés avantageuses qui facilitent la régie d'irrigation de la culture tout en permettant d'en tirer des rendements élevés. Cependant, leur utilisation comporte de nombreux désavantages aux niveaux économiques et écologiques et de nombreux efforts de recherche sont actuellement investis afin de fournir aux producteurs des substrats alternatifs qui offriraient des rendements similaires, tout en diminuant les coûts d'achat et en réduisant l'empreinte écologique de la culture en serre. À ce niveau, les mélanges de sciures d'épinette blanche (*Picea Glauca*) et de tourbe brune suscitent un intérêt grandissant. De récentes études (Juneau et al., 2006;

Lemay, 2006; Bégin, 2008; Allaire et al, 2005) ont démontré qu'ils possédaient des propriétés physiques et chimiques adéquates pour la culture de la tomate et permettaient l'obtention de rendements élevés. Cependant, certains problèmes ont été relevés en ce qui a trait à la régie d'irrigation et à l'accumulation de sels dans ces substrats de culture (Lemay, 2006). Une meilleure compréhension de l'évolution de la salinité des mélanges sciures tourbe en cours de culture ainsi que des phénomènes physiques et chimiques associés au transport des solutés dans ce type de substrats est nécessaire pour remédier à ces problèmes.

CHAPITRE 1 : REVUE DE LITTÉRATURE

1.1 SUBSTRATS DE CULTURE POUR LA TOMATE DE SERRE

1.1.1 Définition générale

Pour être considéré efficace, un substrat de culture se doit de répondre aux besoins des plants en ce qui a trait à la disponibilité de l'eau, de l'oxygène et des nutriments tout en s'avérant un milieu propice à l'encrage et au développement racinaire. Il se doit également d'être exempt de tout agent pathogène pour l'espèce cultivée et de présenter un niveau d'acidité idéal (Caron, 2001). On peut diviser ces caractéristiques essentielles d'un substrat en trois principales classes, soient les propriétés physiques, chimiques et biologiques.

1.1.2 Propriétés physiques

Parmi les propriétés physiques d'un substrat, ses propriétés de rétention en eau sont celles qui sont les plus importantes pour définir son potentiel horticole. La courbe de rétention en eau d'un substrat met en relation sa teneur en eau volumique et la force (tension) avec laquelle le sol retient l'eau dans ses pores (Jury et al., 1991). Cette courbe permet d'obtenir de nombreux renseignements très utiles afin de sélectionner un substrat pour une culture particulière. Elle permet entre autres de déterminer la porosité totale (P) d'un sol, soit la fraction volumique de la matrice du sol disponible pour l'eau et l'air. La courbe de rétention permet aussi de déterminer la quantité d'eau retenue dans un sol qui se ressuie sans contrainte après avoir été saturé. On y réfère en tant que capacité au champ ou capacité en pot (θ_{cc}). Il est généralement reconnu que lorsque le potentiel matriciel d'un milieu artificiel est supérieur à -5 kPa, les plants doivent fournir un effort supplémentaire pour s'approvisionner en eau et commence à montrer des signes de stress hydrique. Lorsque le potentiel dépasse -10 kPa, les plantes n'arrivent plus à puiser l'eau du sol suffisamment rapidement (Jury et al., 1991). Ce stress occasionne des pertes de rendement ou de croissance ainsi que des dommages souvent irréversibles. Il est important de noter que ces valeurs sont influencées par le type de plant cultivé et le type de substrat. Ces deux tensions correspondent respectivement aux points de flétrissement temporaire et permanent. La

courbe de rétention permet d'y associer des valeurs de teneur en eau qui sont notés respectivement θ_{ft} et θ_{fp}. Une fois ces valeurs connues, la détermination des réserves en eau utilisable (RU) et facilement utilisable (RFU) est rendue possible. La courbe de rétention en eau permet également le calcul de la proportion d'air présente dans le sol à différentes tensions ou teneurs en eau (Jury et al., 1991). La teneur en air à capacité en pot (θ_a) est d'intérêt particulier et on y réfère par le terme capacité en air puisqu'elle représente la quantité minimale d'air qui sera disponible dans un substrat ressuyé.

L'ensemble de ces paramètres obtenus à partir de la courbe de rétention fournissent donc des informations importantes sur la capacité d'un sol à subvenir aux besoins en eau et en air des plants cultivés et sur la régie d'irrigation qui lui est appropriée (Caron et Nkongolo, 2004). Plusieurs auteurs se sont intéressés à établir des valeurs de référence pour guider les producteurs dans le choix des substrats et leurs pratiques d'irrigation. Il a par exemple été déterminé qu'une RFU optimale se situe entre 0.20 et 0.30 cm^3/cm^3 pour la production de plantes ornementales (De Boodt et Verdonck, 1972). De nombreuses études traitent de la capacité en air (θ_a) nécessaire pour éviter des conditions d'asphyxie racinaire. Cette valeur est d'ailleurs jugée très importante dans le système européen de classification des milieux de culture, le comité européen de normalisation (Caron et Nkongolo, 2004). On s'accorde généralement pour dire que la capacité en air doit être comprise entre 0.10 et 0.30 cm^3/cm^3.

Une autre propriété physique importante pour un substrat est la conductivité hydraulique saturée (K_{sat}), qui correspond à la vitesse maximale à laquelle l'eau se déplace dans un sol ou substrat. En situation de culture, cette valeur détermine l'aisance avec laquelle l'excédent d'eau d'irrigation sera lessivé d'un substrat et permet de quantifier le flux d'eau vers les racines en situation humide (Klute et Dirksen, 1986). La valeur de conductivité hydraulique saturée est directement reliée au nombre et dimensions des pores d'un substrat, mais aussi à la connectivité et tortuosité du réseau poral.

Toutes ces propriétés physiques influent donc sur l'efficacité d'un substrat pour une culture définie. Il est cependant important de noter que la géométrie des récipients utilisé en culture ainsi que les manipulations sur les substrats, notamment les techniques d'empotage

utilisées (Paquet et al., 1993), ont sur ces propriétés une influence considérable. Des méthodes de mesures in situ des propriétés physiques permettraient des estimations plus réalistes pouvant plus facilement être corrélées à divers paramètres de croissance des plants cultivés (Caron et Nkongolo, 2004).

1.1.3 Propriétés chimiques et biologiques

Les propriétés chimiques et biologiques d'un substrat définissent ses possibilités d'interaction avec la solution nutritive appliquée à la culture et son potentiel à être dégradé en cours de culture par les microorganismes qui l'habitent. Les paramètres d'intérêt pour l'utilisation horticole d'un substrat sont sa capacité d'échange cationique (CEC), son pH et son rapport C/N.

La CEC, exprime la capacité d'un substrat d'échanger des cations adsorbés avec des cations présents dans la solution nutritive (Morard, 1995). Il est généralement considéré qu'une CEC faible ou même nulle est souhaitable pour une culture serricole intensive. Un substrat présentant une CEC élevée peut modifier la composition et le pH de la solution nutritive, ce qui peut générer des déséquilibres entre les divers éléments nutritifs nécessaires aux plants et rend difficile le contrôle de la composition de la solution racinaire.

Le pH du substrat est un paramètre important puisqu'il influence celui de la solution nutritive en échangeant avec celle-ci des ions H^+ ou OH^- . Il est généralement ajusté entre 5.5 et 6.5 avant la culture par l'ajout de chaux calcique (Morard, 1995). Ce paramètre doit faire l'objet d'un suivi régulier puisqu'un pH trop acide ou basique de la solution limite l'absorption par la plante de certains éléments nutritifs essentiels.

Enfin, le rapport C/N d'un substrat est un indicateur de la stabilité structurale d'un substrat face à l'action de la microflore. Un faible rapport C/N indique un substrat sujet à la minéralisation de l'azote organique et donc un affaissement de structure et une diminution de porosité en cours de culture alors qu'un rapport C/N élevé combiné à la présence de

composés phénoliques est signe d'une bonne stabilité structurale, mais peur entraîner une immobilisation importante d'azote (Morel et al., 2000).

1.1.4 Propriétés des mélanges sciures-tourbe

Les sciures d'épinette à l'état pur présentent généralement une porosité et une capacité en air élevée située entre 55 et 60 cm^3/cm^3 (Morel et al., 2000). La capacité de rétention en eau de ce matériel est faible et peut s'avérer limitante pour la croissance des végétaux. Sur le plan des propriétés chimiques, elles sont caractérisées par une CEC faible (5-20 meq/100g), un pH près de la neutralité (5.8 à 6.5) et un rapport C/N relativement élevé (250). Ce matériel utilisé seul a tendance à se compacter en cours de culture, ce qui peut générer des conditions d'asphyxie racinaire.

La tourbe est généralement caractérisée par son degré de décomposition selon l'échelle Von Post. La tourbe peu décomposée ou tourbe blonde (H1-H3 sur l'échelle Von Post) est très utilisée en horticulture (Carrier, 1999). Elle possède une forte porosité, soit en moyenne 95 cm^3/cm^3 et une capacité de rétention en eau élevée (Morel et al., 2000). Sa capacité en air se situe généralement aux environs de 0.20 cm^3/cm^3 (Allaire et al., 1996, Caron et Nkongolo, 2004). Sa CEC est moyennement élevée (100-150 meq/100g) et son pH est acide, soit de 2.5 à 4.5 (Bégin, 2008). La tourbe brune est caractérisée par un degré de décomposition plus avancé (H4-H6) sur l'échelle Von Post. On y retrouve donc une plus grande proportion de particules fines que dans la tourbe blonde et donc une densité plus élevée. Au niveau des propriétés physiques, cela se manifeste par de plus faibles porosité, capacité de rétention en eau et capacité d'air que pour la tourbe blonde (Morel et al., 2000). Sur le plan chimique, elle se différencie de la tourbe blonde par une CEC plus élevée, allant jusqu'à 250 méq/100g.

En ce qui a trait aux mélanges, des travaux de Allaire et al. (2005) ont démontré que l'ajout d'écorce à une tourbe modérément dégradée augmentait sa capacité en air (θ_a), mais diminuait légèrement sa RFU et que le mélange résultant s'avérait stable sur une culture de longue durée (250 jours). Des conclusions similaires ont été obtenues pour différents

mélanges sciures-tourbe (Desbiens, 2003; Lemay, 2006). Ce type de mélange vient donc pallier à la faiblesse de chacun de ses ingrédients. Les sciures et écorces étant généralement caractérisées par de faibles capacités de rétention en eau, et les tourbes par de faibles capacités en air (Morard, 1995). Les courbes de rétention obtenues par Lemay (2006) pour des mélanges de 70% de sciures et 30% de tourbe brune et de la laine de roche montrent des porosités similaires pour les deux types de substrats. Les mélanges de sciures et tourbe présentent des capacités en air supérieures à la laine de roche, et une RFU inférieure, mais suffisante pour la culture de la tomate. D'autres études (Juneau, 2004; Allaire et al., 2005) confirment la viabilité pour la culture en serre de la tomate des substrats à base de sciures et de tourbe brune, bien qu'elles révèlent également de possibles lacunes au niveau de la disponibilité de l'oxygène au niveau racinaire.

1.1.5 Principaux avantages des mélanges sciures-tourbe

De nombreuses études ont mis en évidence le potentiel élevé des mélanges à base de tourbe et de sciures ou écorces. Des rendements supérieurs à la laine de roche ont été obtenus avec des mélanges de sciures, tourbe et compost dans les proportions volumiques (60 :30 :10) par Juneau (2004). Des rendements similaires à ceux de la laine de roche ont également été observés fréquemment pour des mélanges de sciures et tourbe ou encore pour ces matériaux utilisés seuls (Allaire et al., 2005; Lemay, 2006; Bégin, 2008; Xu et al., 1995).

Les mélanges à base de sciures et de tourbe possèdent également l'avantage d'être disponible à faible coût, soit environ au tiers de celui de la laine de roche. Cela s'explique du fait que les sciures soient un sous-produit de l'industrie forestière facilement disponibles (Dorais, 2003). La tourbe brune (H4-H6) peut également être considérée comme un sous produit. En effet, la tourbe blonde (H2-H3) est très prisée dans le secteur horticole. Son exploitation nécessite constamment l'ouverture de nouvelles tourbières et entraîne de nombreux problèmes environnementaux. Or, la tourbe brune se retrouve à l'état naturel sous la tourbe blonde et en proportion nettement plus importante, de l'ordre de 4 :1 environ. Son exploitation permet donc une utilisation plus rationnelle de sites existants (Allaire et al., 2005).

Sur une échelle locale, l'utilisation de sous-produits en tant que substrat de culture a également l'avantage de réduire considérablement la quantité d'énergie nécessaire à leur fabrication et transport. Cette économie est substantielle, si l'on considère par exemple que la production de laine de roche nécessite 18.0 MJ/L (Reist et Gysi, 1990), ou encore que les pains de fibre de noix de coco doivent être transportés sur de grandes distances depuis les pays producteurs, dont le principal est le Sri-Lanka. Enfin, les mélanges sciures-tourbes ont l'avantage par rapport à la laine de roche d'être biodégradables, l'élimination de ces substrats en fin de culture en est donc facilitée.

1.2 EFFET DE LA SALINITÉ SUR LA CULTURE DE LA TOMATE DE SERRE

La gestion de la conductivité électrique (CE) de la solution racinaire est un moyen pour le producteur de contrôler la disponibilité de l'eau ainsi que la balance générative et végétative des plants (Sonneveld et Welles, 1988; Holder et Christensen 1989). Cette gestion est principalement réalisée en ajustant la cédule d'irrigation, la CE de la solution nutritive en fonction du stade de croissance et des conditions environnementales, et en ajustant la fraction de solution nutritive lessivée après chaque application. (Ayers et Westcot, 1985; Peterson, 1996; Blanco et Folegatti, 2002). Le maintien d'une CE élevée peut être avantageux pour plusieurs raisons. D'abord, en début de culture cela favorise la fabrication de parois cellulaires résistantes (Dorais et al., 2001). Une CE élevée favorise également une production générative sous des conditions de faible luminosité et d'humidité élevée (Sonneveld et Welles, 1988). La qualité organoleptique peut également se voir améliorée par le maintien d'une salinité élevée de la solution racinaire (Dorais et al., 2001). À ce niveau, des effets bénéfiques sur la qualité du fruit ont été observés pour des valeurs de CE allant jusqu'à 14 dSm^{-1} (Cuartero et Fernandez-Munoz, 1999). Ces effets de la salinité sur la qualité du fruit sont cependant très variables selon les cultivars (Dorais et al., 2001).

Les fortes concentrations en ions associées à une salinité élevée ont comme effet non désirable une diminution du potentiel osmotique de la solution du sol, ce qui diminue la disponibilité de l'eau et peut faire apparaître des effets toxiques de certains ions (Rhoades

et al., 1992). Les propriétés physiques et chimiques (pH, conductivité hydraulique, disponibilité des nutriments) de certains substrats peuvent également être modifiées par de fortes concentrations ioniques dans la solution du sol (Blanco et Folegatti, 2002).

Au niveau des plants, la réduction du potentiel osmotique de la solution nutritive induite par des salinités élevée peut entraîner une diminution de l'absorption d'eau par les racines (Sonneveld et Voogt., 2001; Dorais et al., 2001). Les taux de photosynthèse et de respiration des plants ainsi que le potentiel du xylème de la feuille sont également affectés par la salinité du milieu racinaire (Xu et al., 1995), tout comme la production de fruit est également affectée par la CE du substrat. On note généralement une diminution significative du calibre des fruits lorsque la salinité de la solution racinaire s'élève au-delà d'un certain seuil, variant de 2.0 à 6.5 dSm^{-1} selon les auteurs (Dorais et al,. 2001; Xu et al., 1995; Cuartero et Fernandez-Munoz, 1999). Ces mêmes sources rapportent des diminutions des rendements vendables allant de 10 à 15 % par unité de CE au-delà des seuils proposés.

1.3 MOUVEMENTS DE SOLUTÉ DANS LES SUBSTRATS DE CULTURE

1.3.1 Distribution des sels dans les substrats de culture

Des études démontrent que les substrats à base de tourbe sont sujets à une élévation progressive de leur CE en cours de culture (Lemay, 2006; Xu et al., 1995). Pour d'autres types de substrats comportant une CEC similaire, une accumulation des sels plus importante à la surface du substrat qu'en profondeur a été observée dans plusieurs études (Blanco et Folegatti, 2002; Badr et Taalab, 2007). Cet effet peut être attribué au prélèvement racinaire et à l'évaporation de surface (Blanco et Folegatti, 2002; Raats, 1975; Sonneveld et Welles, 1988) ou encore aux patrons de distribution de solution nutritive inégaux générés par les systèmes de goutteurs (Badr et Taalab, 2007).

1.3.2 Modèle d'écoulement mobile-immobile

Combiné à des outils de calculs informatiques, l'utilisation de modèles de transport de solutés peut permettre d'expliquer ou de prédire les mouvements de sels dans des substrats

de culture en fonction de leurs différentes propriétés sans avoir à procéder à de longues et coûteuses procédures expérimentales.

Le concept d'eau mobile-immobile (MIM) a été développé en 1964 par Coats et Smith dans le domaine de l'ingénierie pétrolière pour être étendu au transport de soluté dans le sol par van Genuchten et al. (1977). Ce modèle avait comme fondement une meilleure description des phénomènes de transport préférentiel. À l'époque, le modèle de transport le plus utilisé était le modèle advection-dispersion (CDE), mais des études ont mis en évidence sa faiblesse à décrire les transports de soluté dans les milieux poreux comportant une importante distribution de dimensions de pores et une tortuosité élevée (van Genuchten et al., 1977; Clothier et al, 1992; Clothier et al., 1995; Jaynes et al, 1995).

Il est basé sur le principe que l'eau du sol est divisible en deux fractions, l'une mobile, l'autre immobile. Dans la phase mobile, l'eau et le soluté se déplacent selon une certaine vitesse par des processus d'advection et de diffusion alors que dans la phase immobile l'eau est essentiellement stagnante et les seuls mouvements de solutés sont des échanges diffusifs avec la phase mobile.

Comme le modèle CDE, le modèle MIM est basé sur l'équation de continuité, ici présentée pour un écoulement vertical uniquement.

$$\frac{\partial G}{\partial t} = -\frac{\partial J}{\partial z} \qquad (1)$$

Où : G = qté de matière (masse, concentration ou énergie)

J = flux de matière ([masse, concentration ou énergie] / unité de surface x temps)

z = position verticale

t = temps

Le modèle MIM appliqué au transport de soluté implique cependant des définitions des termes G et J différentes de celles du CDE. Ces définitions sont exprimées par les équations

(2) et (3). Les indices *m* et *im* font respectivement référence aux phases mobiles et immobiles.

$$G = c_m\theta_m + c_{im}\theta_{im} \quad \text{avec} \quad \theta = \theta_m + \theta_{im} \tag{2}$$

$$J = J_m + J_{im} \quad \text{avec} \quad J_m = \theta_m D_m \partial c_m / \partial z + \theta_m v_m c_m \tag{3}$$

$$\text{et} \quad J_{im} = 0$$

Où : θ = teneur en eau volumique (L^3L^{-3})

c = concentration (ML^{-3})

D = coefficient de dispersion hydrodynamique (L^2T^{-1})

v = vitesse d'écoulement (LT^{-1})

θv = q = flux de matière ($ML^{-2}T^{-1}$ ou $L^3L^{-2}T^{-1}$)

En substituant (2) et (3) dans (1) et en postulant un régime permanent, on obtient :

$$\theta_m \frac{\partial c_m}{\partial t} + \theta_{im} \frac{\partial c_{im}}{\partial t} = \theta_m D \frac{\partial^2 c_m}{\partial z^2} - q_m \frac{\partial c_m}{\partial z} \tag{4}$$

En postulant un transfert de masse diffusif de premier ordre entre les phases mobiles et immobiles, on peut remplacer le second terme de (4) par :

$$\theta_{im} \frac{\partial c_{im}}{\partial t} = \theta_m \propto (c_m - c_{im}) \tag{5}$$

Où : α est le coefficient d'échange de masse (T^{-1})

Les expressions (4) et (5) sont donc les équations représentant le modèle MIM pour un écoulement unidirectionnel en régime permanent. Étant donnée la structure complexe du réseau poral des substrats à base de tourbe (pores occlus, forte tortuosité), il a été démontré que le modèle MIM s'applique particulièrement bien à ce type de substrat (Hoag et Price, 1997; Ours et al., 1997). Une présence importante d'eau immobile pourrait selon les mêmes auteurs y occasionner du retard dans le transport de soluté.

1.4 OBJECTIFS ET HYPOTHÈSES

Ce projet a comme objectif principal de répondre à la problématique d'accumulation de sels dans les substrats organiques utilisés pour la culture de serre. Les objectifs spécifiques de cette étude sont 1) comparer les rendements de tomates obtenus avec des mélanges sciures-tourbe à ceux obtenus avec la laine de roche et la fibre de coco 2) réaliser un suivi de l'évolution de la salinité dans différents substrats en cours de culture 3) et de vérifier la présence d'une phase d'eau immobile dans les mélanges à base de tourbe et en quantifier l'importance dans le phénomène d'accumulation des sels.

Les hypothèses de départ de l'étude sont que 1) les mélanges sciures-tourbe permettent l'obtention de rendements supérieurs ou égaux à la laine de roche et la fibre de coco 2) les mélanges sciures-tourbe comportent une fraction d'eau immobile plus importante que la laine de roche et la fibre de coco 3) l'accumulation de sels dans les substrats de culture est expliquée par la présence d'une phase d'eau immobile.

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CHAPITRE 2 : SALTS ACCUMULATING IN ORGANIC GROWING MEDIA USED IN A GREENHOUSE TOMATO PRODUCTION : AN IMMOBILE PHASE

RÉSUMÉ

Quatre substrats organiques (mélanges de sciures et tourbe) et deux substrats de référence (laine de roche et fibre de coco) ont été évalués dans une expérience de production à long terme de la tomate en serre. Les récoltes en fruits ont été évaluées et un suivi de la conductivité électrique (CE) de la solution du sol et des eaux de lessivage a été réalisé. En fin de culture, la CE des substrats a été mesurée à trois profondeurs différentes. Les propriétés physiques initiales des substrats ont également été évaluées. Les résultats ont montré que la CE de la solution racinaire a été supérieure à la valeur critique pour la production de fruit de 4.5 dSm^{-1} pour la plus grande partie de l'expérience. À la fin de l'expérience des valeurs de CE élevées ont été obtenues pour des échantillons pris à la surface de mélanges sciures-tourbe. Pour ces mêmes substrats, une tendance voulant que la CE diminue avec la profondeur d'échantillonnage a été observée. La tendance inverse a été observée pour la laine de roche. Au niveau des rendements, aucune différence significative n'a été observée. Une expérience de lessivage en régime permanent a également été réalisée avec des substrats préalablement utilisés dans une serre commerciale. Des phénomènes de retard et d'étirement des courbes de fuite de transport de soluté ont été observés, ce qui est typique de substrats comportant une phase d'eau immobile importante. Ces résultats suggèrent qu'une meilleure compréhension des mécanismes de transport de soluté dans les mélanges sciures-tourbe et la fibre de coco est nécessaire pour une meilleure gestion de la salinité et de meilleurs rendements.

ABSTRACT

Four organic media (peat-sawdust mixtures) and two reference media (rockwool and coconut coir) have been evaluated in a long term greenhouse tomato production experiment. In addition to tomato yields, the electrical conductivities (EC) of the soil solution and leachate were monitored throughout the experiment. At the end of the experiment, the media's bulk EC were evaluated at three different depths and the yields were compared. The media's initial physical properties were also evaluated. Results show that for all organic media and coconut coir, EC of the soil solution remained above the threshold value of 4.5 dS/m for fruit productivity for most of the experiment. At the end of the experiment, high values of EC were obtained from samples taken near the surface for the peat-sawdust media, with a general trend of EC decreasing with sampling depth. The opposite trend was noticed for rockwool. Yield measurements showed no significant difference between any media. In another experiment, samples of one the previously mentioned peat-sawdust growing medium and coco fiber have been taken at the end of a tomato production cycle in a commercial greenhouse. A laboratory leaching experiment have been conducted to obtain solute breakthrough curves (BTCs) during the leaching process. BTCs of both media showed an important tailing and retardation, typical of dual porosity type media in which an important immobile water phase is present. These results suggest that a better understanding of solute transport in peat-sawdust mixtures and coco fiber could lead to a better salinity management and higher yields.

INTRODUCTION

Around the world, about 70% of the fresh water taken from surface and groundwater is used for food production through irrigation. Irrigation has significant economical impacts. As an example, half the value of total crop sales in the United States is grown on irrigated farms, which account for only 16% of total harvested cropland (USDA, 2005). Water use in agriculture also implies lots of environmental concerns. Worldwide, most of the irrigation systems are open, which implies that a third to a half of the applied water is lost in the environment. This often leads to pollution of ground and surface waters by fertilizers (Hagin and Lowengart, 1996). The greenhouse industry shares its part of responsibility as very important quantities of water and fertilizers, up to 50 000 l/ha, are rejected daily to the environment (Fricke, 1998). For sustainable development, efforts must be made to improve water and fertilizer use efficiency in the greenhouse industry.

Soilless culture accounts for 90% of the greenhouse fruit/vegetables production in North America (Lemay, 2006). The most popular growing media for that type of production are rockwool and coconut coir slabs. Both these substrates require frequent application of nutrient solution (Sonneveld et al., 2001). As an alternative, organic media composed of moderately decomposed peat and sawdust have proven efficient for greenhouse tomato production. Available at low costs, they provide yields comparable to rockwool and coconut coir and tend to minimize fertilizer and water use (Lemay, 2006; Juneau et al., 2006; Allaire et al., 1996; Allaire et al., 2005; Bégin, 2008).

Irrigation management in these organic media has yet to be optimized in order to improve crop quantity and quality, and salt accumulation in the substrate has been pointed out as one of the main problem associated with the use of peat based growing media. (Lemay, 2006; Xu et al,. 1995). It has been frequently reported that high salinity levels lead to decreases in tomato yields and fruit quality (Dorais et al., 2001). A better understanding of the mechanisms of salt accumulation in organic growing media is therefore required.

Surface evaporation and uneven distribution of nutrient solution from dripper irrigation systems have been reported to induce salinity build-up in different growing media (Raats, 1975; Badr et Taalab, 2007). Another possible explanation is the presence of an immobile water phase in peat which would induce retardation in solute transport (Hoag and Price, 1995, Ours et al., 1997).

The objectives of this study are 1) to verify the suitability of four different peat based substrates for greenhouse tomato production (physical properties and yields) 2) to monitor the evolution of salinity in different growing media during a long term greenhouse production experiment and 3) to investigate the presence of an immobile water phase in the peat based substrates.

MATERIAL AND METHODS

Experiment A

Experimental setup

The experiments were conducted in a randomized block design. Six growing media treatments were used in this study. The experimental unit consisted of two containers/bags/slabs of each media containing four tomato plants. The experiment was conducted in six replicates for yield measurements, and three replicates for initial physical properties and salinity measurements. Results were analyzed with standard ANOVA procedures, simple contrasts and LSD multiple comparison tests. All the measurements were performed between June 2008 and January 2009.

Growing media

Two organic media and two control substrates were studied in this experiment. For the organic media, two container types and the addition of a microbial agent were also evaluated. Overall, 6 treatments differing by medium composition, and/or container type and/or biological agent addition were studied (Table 1). For the organic media (*SP-C, SPb-B, PS-C, SP-B*), two different mixtures of peat with a degree of decomposition of H4-H5 on

the Von Post scale and white spruce (*Picea glauca*) sawdust (Premier Horticulture Ltée, Riv.-Du-Loup, Qc, Can) were used. In all these cases, sawdust particles size ranged from 2 mm to 6 mm and peat particles size ranged from 0.5 to 25 mm. The pH of these substrates was adjusted to approximatively 5.5 by an addition of fine calcitic lime. For treatments *SP-C*, *SPb-B* and *SP-B*, volumetric proportions of peat and sawdust were 30:70, and they were 70:30 for treatment *PS-C*. Treatments *SP-C* and *PS-C* were placed in rigid 29.5cm x 39.5cm plastic containers with a 13 cm depth. Two sections (Fig. 1) act as a reservoir of free nutrient solution, thus allowing upward water movement by capillary rise. Treatments *SPb-B* an *SP-B* were placed in plastic bags that were held in place by 29.5x39.5x13cm plastic supports, and differed only by the addition of a microbial agent (*Bacillus* sp.) in treatment *SPb-B*. As controls, treatment *Rckwl* was a standard rockwool slab (Growtop Master, Grodan) and *Coco,* a coconut fiber slab (Biogrow duo).

Initial physical properties

All the physical properties measurements presented in this section were performed only for the substrates of different composition (*Rckwl*, *Coco*, *SP-C* and *PS-C*). Since they were performed in laboratory (in opposition to *in situ measurements*) it was assumed that the container type and the addition of microbial agent had a negligible effect on the substrates' physical properties.

Three polyvinyl chloride (PVC) cylinders (150 mm height and 133 mm internal diameter) of treatments *Rckwl*, *Coco*, *SP-C* and *PS-C* were manually packed for a total of 12 cylinders. A wire netting with a 1.0 mm mesh was fixed at the lower boundary of the cylinders to prevent material loss. For the treatments *SP-C* and *PS-C*, the material was slightly hydrated with distilled water and poured into the cylinders to the top limit. The cylinders were then dropped three times from a 10 cm elevation onto a hard horizontal surface. The space made available on the top part of the cylinders due to material compaction was then filled with loose material. For treatment *Coco*, a 133-mm diam. disc was cut from a dehydrated coconut coir slab and put into a cylinder. It was then slowly hydrated from bottom up with distilled water causing the material to expand to a height

between 125 and 135 mm. Available space on top of the cylinder was filled with independently humidified loose material. For treatment *Rckwl*, two 133 mm diam. disc were cut from a rockwool slab and inserted on top of each other in a cylinder, making sure that no empty spaces were left between the discs and between the discs and the cylinder wall. In this particular case, the height of the medium in the cylinder was 140 mm. For all treatments, this procedure allowed to mimic the media's bulk densities in greenhouse conditions at the beginning of production.

After a slow saturation from the bottom with tap water, measurements of the media's saturated hydraulic conductivity were conducted with the Constant Head method (Reynolds, 2008). The cylinders were then placed onto tension tables in order to obtain their water retention curves for sorption and desorption as well as their unsaturated hydraulic conductivity functions following the methods described in CPVQ (1990). The CPVQ method was slightly modified to allow simultaneous determination of the water retention curve and the unsaturated hydraulic conductivity curves. The exact procedure and instrumentation is described in Bonin (2009). From the water retention curves, values of saturated water content (θ_s), container capacity (θ_{cc}), air filled porosity (θ_a) and easily available water (EAW) were calculated as described in Jury et al. (1991).

After these procedures, 50 ml substrate subsamples were taken from cylinders of treatments *Coco*, *SP-C*, and *PS-C* and placed in a 550°C oven for 16h in order to evaluate their organic matter fraction (f) and total porosity (P) with the method described in CPVQ (1990).

Crop management

The experiment took place in the high performance experimental greenhouse complex at Université Laval and was conducted between June and December 2008. Tomato plants of Starbuck cultivar grafted on Beaufort rootstock initially seeded in rockwool cubes were transplanted in the experimental growing media on June 5th 2008. Before transplant, all growing media had been saturated for a 24h period with a standard nutrient solution. Before saturation, Coconut fiber slabs had been slowly hydrated with a Calcium nitrate solution as

recommended by the product manufacturer. During a seven month period, standard cultural and environmental control procedures for greenhouse tomato production were carried out. Average daily and night time temperatures were respectively 25°C and 18°C. Supplemental lighting was provided between 6h and 20h with high density sodium lamps when PAR value in the greenhouse was below 1200 $\mu molm^{-2}s^{-1}$. Standard nutritive solution with and EC ranging from 2.2 to 3.5 dSm^{-1}, with an average of 2.8 dSm^{-1} and pH ranging from 5.0 to 6.0 was provided to each treatment through completely independent drip irrigation systems. Fertigation was automatically triggered by a computer program (Priva Intégro [725.1 UK], Priva B.V., Netherlands) based on readings of the matric potential at mid-height of the media realized with automated wireless tensiometers (Hortau, St-Romuald, Qc, Can). Fertigation setpoints for each treatment were chosen based on previous studies in similar media by Lemay (2006). Leaching fraction of the applied fertilizer solution ranged from 30 to 40% on sunny days and from 15 to 25% on cloudy days. From the 8th week of production to the end of the experiment, the marketable yields were collected and weighted for six repetitions of all treatments twice weekly.

Salinity measurements

On a weekly basis, 10 to 20 ml samples of soil solution were taken from three replicates of all treatments. Samples were collected by exerting a 5.0 to 6.0 kPa tension with a succion lysimeter whose porous cup was inserted at mid-height of each growing media. In the case of treatment *Rckwl* the samples were collected with a hypodermic needle inserted at mid-height of the substrate. The EC of these samples was determined with a conductivity meter directly in the collected solution.

The effluent (leachate) from the containers, slabs or bags in which the soil solution samples were taken was collected daily in plastic containers placed under the growing tables. Every day at the end of the irrigation period, the volume of this effluent was measured with a graduated cylinder and its EC was measured with a portable conductivity meter. Data from the effluent and soil solution were compared for the days both measurements were conducted.

At the end of the tomato production, 250 ml samples of growing media were taken at three different depths (1/4, ½ and ¾ of the media's height) for the organic treatments and at two depths (1/3 and 2/3 of the medium's height) for *Rckwl*. The EC of these samples were determined with a conductivity meter after the soil solution was extracted by the SSE method (CPVQ, 1990).

Experiment B

Sample collection

For a one year period starting in July 2008, two of the growing media from experiment A (*Coco* and *SPb-B)* were tested in a commercial greenhouse under normal crop and irrigation management. The experimental setup included 74 recipients or slabs of each growing media disposed in two rows which were separated by one border plants row. A standard fertigation solution was provided independently to both treatments through a drip irrigation system. Like in experiment A, irrigation was triggered by an automated system based on real-time measurements of the substrates matric potential.

Three undisturbed samples of each treatment (growing media and roots) were randomly sampled at the end of the production period. Columns of 133 mm diameter were carefully extracted from the selected recipients or slabs and inserted into PVC cylinders prepared identical to those used in experiment A.

Leaching experiment

Adjusting the leaching fraction of a fertilizer solution is a common way for growers to avoid salt accumulation in a growing media. This experiment was designed to obtain a better understanding of the solute transport behavior of the two media (*Coco* and *SPb-B*) during a leaching process.

The cylinders described earlier were placed on the apparatus shown in Figure 2, which allowed the application of a fertilizer solution by aspersion on top of the cylinder, as well as

the collection of the effluent from the substrate. At a constant rate (between 6 and 8 ml/min), a nutrient solution with an EC of 2.2 dSm^{-1} and whose composition is given in (Table 2) was applied on top of the cylinders. At regular time intervals, the effluent from the cylinders was collected in glass recipients. Volume and EC measurements were performed on the effluent. When the EC of the effluent reached the value of the input solution, the latter was switched to distilled water, with the application rate remaining unchanged. The volume and EC measurements on the effluent were maintained during that phase. The leaching with distilled water was performed until the EC of the effluent became close to zero or until it stopped decreasing for an extended period of time. More details about this experimental procedure are provided in Létourneau (2010).

Solute breakthrough curves (BTCs) during leaching were generated by plotting the EC of the effluent in function of the effluent's cumulative volume. The EC value of the effluent was assumed to represent the EC of the soil solution (a flux concentration) at the lower end of the column for further analysis.

Parametric fitting

BTCs representing the leaching with distilled water phase were fitted with an analytical solution to the mobile-immobile solute transport model (MIM) developped by Toride et al. (1995) but adapted to experimental conditions using the Mathcad software (Parametric Technology (Canada) Ltd. - Montreal). According to the MIM, the transport of a conservative solute for a 1D steady-state flow can be expressed as :

$$\theta_m \frac{\delta C_m}{\delta t} + \theta_{im} \frac{\delta C_{im}}{\delta t} = \theta_m D_m \frac{\partial^2 C_m}{\partial z^2} - q \frac{\delta C_m}{\delta z} \quad [1]$$

where θ_m and θ_{im} $[L^3L^{-3}]$ are the mobile and immobile volumetric water contents, C_m and C_{im} $[ML^{-3}]$ are the solute concentrations in the mobile and immobile regions, D_m $[L^2T^{-1}]$ is the hydrodynamic dispersion coefficient, t [T] is time and z [L] is depth, q $[LT^{-1}]$ is the Darcian water flux density and can also be expressed as

$$q = v\theta_m \qquad [1.1]$$

were v is the pore water velocity [LT^{-1}]. Exchange between the mobile and immobile regions can be written as per Eq. [2].

$$\theta_{im} \frac{\delta C_{im}}{\delta t} = \alpha(C_m - C_{im}) \qquad [2]$$

where α [T^{-1}] is a first order mass exchange coefficient between the mobile and immobile regions. Time dependant effluent concentration data were fitted for v, D_m, θ/θ_{im} and α, assuming that experimental data was the concentration in the mobile C_m [ML^{-3}] phase at a 15 cm depth and that the initial mobile concentration C_0 [ML^{-3}] was the concentration of the fertigation solution used for the initial leaching phase. A minimization of the sum of square errors (SSE) between experimental and fitted data procedure was used to improve the accuracy of the results. In this experiment, no retardation factor was fitted since those substrates have a low CEC and a low bulk density, which is comparable to a pure soil (See results and discussion and Table 3).

RESULTS AND DISCUSSION

Experiment A

Physical Properties

The initial physical properties of the growing media are presented in Figures 3 and 4, and Table 3. Note that these results represent the properties of the raw materials. They give important information about a substrate's suitability for tomato production, but may be subject to change according to potting techniques and cultural practices (Caron et al. 2004).

The water retention curves presented in Figure 3 showed two different types of behavior during desorption. For *Rckwl* water content quickly drops with increasing matric potential (ψ) and the substrate was almost completely drained when ψ reached –3 kPa. That kind of

behavior is comparable to that of a coarse sand, but with a general shift upward in water content. For the organic substrates (*Coco, SP-C* and *PS-C*) after a steep drop from saturation (θ_s) to container capacity (θ_{cc}), the water content decreased almost linearly at a much slower rate, which is typical for organic substrates. These curves already show that irrigation management must be adapted depending on the growing media. Since it has less available water and a lower total volume, rockwool has to be irrigated more often than the organic substrates.

Figure 4 presents the evolution of the hydraulic conductivity ($K(\psi)$) as a function of the substrates matric potential for treatments *Coco, SP-C* and *PS-C*. Unfortunately, results from rockwool could not be presented because the instruments that were used for data collection did not work properly in that medium. At first, all the substrates behaved similarly, their $K(\psi)$ decreasing from $\sim10^{-2}$ to $\sim10^{-7}$ ms^{-1} with ψ increasing from -1 to -5 kPa. Within this range of matric potential (corresponding to a proper irrigation management) and for all substrates these $K(\psi)$ values meet the average daily evapotranspiration demand for a greenhouse tomato production ($\sim$4 mmd^{-1}). At ψ values lower than -5 kPa, $K(\psi)$ decreased at a slower rate for treatment *PS-C* than for treatments *Coco* and *SP-C*. This can be explained by the higher water content at these matric potentials in this substrate containing a high peat proportion. For the saturated hydraulic conductivity (K_{sat}), the highest value was observed in treatment *SP-C* (8.6×10^{-2} ms^{-1}), intermediate values were obtained for treatments *Rckwl* and *Coco*, and treatment *PS-C* yielded the lowest value (2.0×10^{-2} ms^{-1}). All these values are within the range recommended for a growing medium.

The data from the water retention curves allowed the calculation of some physical parameters presented in Table 3. Looking first at the saturated water content (θ_s), all 4 substrates behaved similarly with θ_s values ranging from 0.92 to 0.98 cm^3cm^{-3}. Within this short range, rockwool (mineral) was significantly different from the other treatments (organic). More important differences are visible for the water content at container capacity (θ_{cc}). Once again rockwool significantly differed from the organic materials with a θ_{cc} of 0.76 cm^3cm^{-3}. This represents approximately a 40% increase compared to the mean value

for the organic substrates. Within the organic treatments, treatment *SP-C* showed a θ_{cc} significantly lower than *Coco* and *PS-C*.

These results have a direct effect on the calculated values of air filled porosity (AP) and easily available water (EAW). Rockwool significantly differed from the organic substrates with the highest EAW (0.76 cm^3cm^{-3}) and lowest AP (0.22 cm^3cm^{-3}) values. Intermediate values were observed for *Coco* and *PS-C* (EAW≈0.22 cm^3cm^{-3}; AP≈0.35 cm^3cm^{-3}). *SP-C* significantly differed from the other organic materials with lower EAW (0.11 cm^3cm^{-3}) and higher AP (0.49 cm^3cm^{-3}). Although the four treatments provided a wide range of values for these parameters, all these results are within the limits of generally recommended values for horticultural substrates (Caron et al., 2008). The only exception is treatment *SP-C,* which may have an excessive drainage capacity.

In summary, these results confirm that the peat-sawdust growing media have physical properties that make them suitable for horticultural purposes. Although very different from that of rockwool, their behavior showed to be very close to that of coconut fiber, a commonly used substrate in the industry. They also confirmed that irrigation management must be specially adapted to those substrates in order to use them efficiently.

Salinity of soil solution and leachate

Figure 5 presents the electrical conductivities (EC) in the soil solution compared to the EC of the leachate from the growing media. It can be seen in general for all treatments but *Rckwl* that both values were close in the early stages of production, and that at some point, depending on the treatment, the EC value in the soil solution became higher than the value in the leachate. For treatments *Coco*, *SP-C*, *PS-C* and *SP-B*, that spread was observed to increase during the experiment. At the end of production the EC value in soil solution was 8 to 40% higher than in the leachate for treatments *Coco*, *SP-C*, *PS-C* and *SP-B*. In the case of treatment *SPb-B*, both EC values were quite close throughout the experiment.

For the mineral treatment (*Rckwl*), the opposite trend was observed. Early in the experiment, the EC values in the soil solution were about 35% lower than in the leachate. That spread diminished throughout out the production, and at the end of the experiment, the EC in the soil solution was around 13% lower than in the leachate.

As shown in Figure 6, the salinity level in the soil solution was around the tomato productivity threshold of 4.5 dSm^{-1} (Dorais et al., 2001) for most of the experiment for treatments *Coco*, *SP-C*, *PS-C* and *SP-B*. Despite regular leaching, EC values raised up to 6.9 dSm^{-1} in *PS-C* and 11.0 dSm^{-1} in *Coco* in the last stages of the experiment. For treatments *Rckwl* and *SPb-B*, EC of the soil solution reached the threshold value after respectively five and six months of production but for these two treatments, the final EC in the soil solution were observed to be below the threshold value. Statistical analysis showed no significant differences between any of the treatments regarding their final EC values.

These results suggested that in peat-sawdust mixtures (except treatment *SPb-B*), salinity levels may sometimes rise in the soil solution during tomato production at levels that may negatively affect plant growth and fruit production. However, a relatively good salinity control is possible in the peat-sawdust mixes since for all treatments, it was possible to maintain the EC of the soil solution between 3.0 and 6.0 dSm^{-1} during most of the experiment and to avoid extreme EC values. No clear distinction can be made between the behaviors of coconut fiber and both peat-sawdust mixtures. As treatments *SP-C* and *SP-B* behaved similarly, it can be said that the container type in this case did not really affect salinity build-up in the substrates. It seems although that the addition of a microbial agent had an effect on salt levels in the soil solution, as the differences in EC between the soil solution and the leachate were in most replicates greater (not significantly according to a student-t test) in *SP-B* than in *SPb-B* by the end of the production period (Figure 5). This leads to the hypothesis that biochemical processes due to microbial activity might play a role in salt accumulation in the substrates. More experiments are required to verify the validity of that hypothesis.

Salinity at different depths

Figure 7 presents the EC at three different sampling depths from SSE extracts performed at the end of the experiment. Statistical analysis of these results showed no significant effect of medium composition, but very significant effects ($p < 0.0001$) of sampling depth and of the interaction between sampling depth and medium composition (Table 4a). The decomposition of this interaction into its main effects by simple main effect contrasts showed that the effect of sampling depth was very significant for treatments *Rckwl*, *SP-C*, *PS-C* and *SP-B* and not significant in treatment *SPb-B* and *Coco* (Table 4b).

Considering the variation of EC with sampling depth, three different trends were noticeable. First, in *Rckwl*, salinity levels significantly increased with sampling depth. This was surprising for a mineral medium with a low CEC per unit volume. These results could possibly be explained by the fact that after irrigations, the applied nutritive solution remained for a long period in the plastic bag covering the slabs.

In the case of treatments *SP-C*, *PS-C* and *SP-B*, EC values decreased with sampling depth (Figure 7). That difference was particularly pronounced in treatment *PS-C*. For treatments *SP-C* and *PS-C*, surface evaporation and capillary rise could be logical explanations for this phenomenon. The top of the substrate was directly exposed to atmospheric conditions and the water storage sections of the plastic containers (Figure 1) allowed upward nutritive solution via capillary rise. Due to the low values of unsaturated hydraulic conductivity in these substrates (Figure 4), the hypothesis of surface evaporation is more plausible.

Finally, no significant difference between ECs at different sampling depths was obtained for treatments *Coco* and *SPb-B*. In the case of *Coco*, this could be explained by the fact that almost no evaporation could take place because of the plastic bag surrounding the slab. The low specific surface of the coarse coconut fibers also diminishes the sorption capacity of that medium. Treatment *SPb-B* was subject to the same atmospheric conditions than treatment *SP-C*, *PS-C* and *SP-B*, but evaporation does not seem to have caused an elevation

of salinity near the surface of the substrate. Once again it is possible that microbial activity due to the addition of *Bacillus* sp. might have influenced the salt accumulation processes.

Tomato Yields

For all treatments, the fresh weights of marketable fruit were compiled from July to December 2008 and the cumulative weights are presented in Figure 8. No significant differences could be observed between any of the treatments, as marketable tomato yield ranged from 23.48 to 25.46 kgm^{-2}. These results are consistent with observations by Lemay (2006) and Juneau et al. (2006), in which peat based media provided yields comparable to rockwool.

In summary, experiment A allowed to observe that a relatively good salinity control in the soil solution was possible in peat-based substrates. Salt accumulation did occur and some salinity peaks were observed throughout the production period, but that did not significantly affect tomato yields. Coconut fiber and peat-sawdust mixes had in common a pronounced salinity build up (in comparison with rockwool), but also presented a different vertical distribution of salts at the end of the experiment.

For the peat-sawdust mixes, surface evaporation and, as mentioned earlier, biochemichal reactions induced by the presence of micro organisms can be pointed out as phenomena possibly responsible for salt accumulation. It is also generally accepted that peat has a dual porosity matrix, in which the presence of an immobile water phase could induce important solute retardation and accumulation (Hoag and Price, 1997; Ours et al., 1997). Since many similarities were observed in the physical properties of coconut fiber and the peat-sawdust mixes, it is possible that the same phenomenon could affect solute transport in coconut fiber. Unequal distribution of the nutritive solution in the substrates from a drip irrigation system is another possible explanation for the accumulation of salts and their vertical distribution. Experiment B, in which the presence of an immobile water phase and the influence on leaching efficiency of a uniform solute application was designed to further investigate the importance of these last two phenomena.

Experiment B

The data collected during the leaching experiment allowed to produce the breakthrough curves presented in Figure 9. The results were quite variable during the leaching with a nutrient solution phase, especially for coconut fiber. This can be in part explained by the high variability of environmental conditions in the commercial greenhouse (as compared with the experimental greenhouse of experiment A, which lead to great differences in the substrate salinity level by the time samples were taken. From these results, it can be observed that variation of the EC as a function of the applied solution or distilled water volume is highly non linear. The amount of nutrient solution required to bring the EC of the effluent at the value of the input solution (2.0 dSm^{-1}) ranged from 2000 to 8000 ml. In general, larger amounts of solution were required for the peat-sawdust mixture than for coconut fiber. The initial EC of the substrate was also generally higher in the peat-sawdust mix.

Considering the leaching with distilled water phase (Figure 10), both treatments behaved similarly during all repetitions. An average of 2500 ml of distilled water was required to reach a plateau in the EC value of the effluent. In all cases the final EC ranged from 200 to 500 μScm^{-1} and could not be brought back to zero. That part of the BTCs is consistent with predictions from solute transport models.

The experimental data points were fitted with a curve modeling the analytical solution to the MIM (Figure 11). The sum of square errors (SSE) between fitted and experimental points ranged from 4.59×10^{-4} to 8.69×10^{-3}. The minimal SSE that can be obtained from this fitting procedure is 1×10^{-6} with theoretical data sets. The fitted parameters are presented in Table 5. While the results from both substrates were not statistically different for v, D and α, they strongly differed for the ratio of immobile to total water content (θ_{im}/θ). The peat-sawdust mix presented an immobile fraction more than twice as important as in coconut fiber with average ratios of respectively 53% and 20%. These values are high, and could partly explain salt accumulation in these substrates. In theory, high immobile water content is linked with important physical nonequilibrium, which implies that solutes are most likely to diffuse from the mobile to the immobile water phase. Since no advective

transport processes are possible in the immobile water phase, it makes leaching of accumulated solutes more difficult to achieve. At this point it is not known if these high immobile water ratios are inherent to these two substrates or influenced by interactions with roots, microorganisms and/or the nutrient solution during tomato production. The importance of physical equilibrium as compared to surface evaporation and microbial activity also needs to be further investigated. More experiments with a better control of the initial conditions are required to obtain these clarifications.

CONCLUSION

This experiment confirms that peat-sawdust mixtures are a viable and promising substitute to rockwool. Irrigation management with these substrates still needs to be improved, but they have shown to possess the physical properties required for horticultural production. Even if the EC of the soil solution was sometimes higher than the tomato productivity threshold during the production period, the peat-sawdust mixtures provided marketable yields comparable to those of rockwool and coconut fiber. Results suggested that salinity build-up in peat-sawdust mixtures is may caused, among other factors, by the presence of an important immobile water phase (physical nonequilibrium). Being able to avoid salinity build-up in these substrates could lead to better performances and thus, a better understanding of the mechanisms of salt transport and accumulation in peat-sawdust mixtures is necessary.

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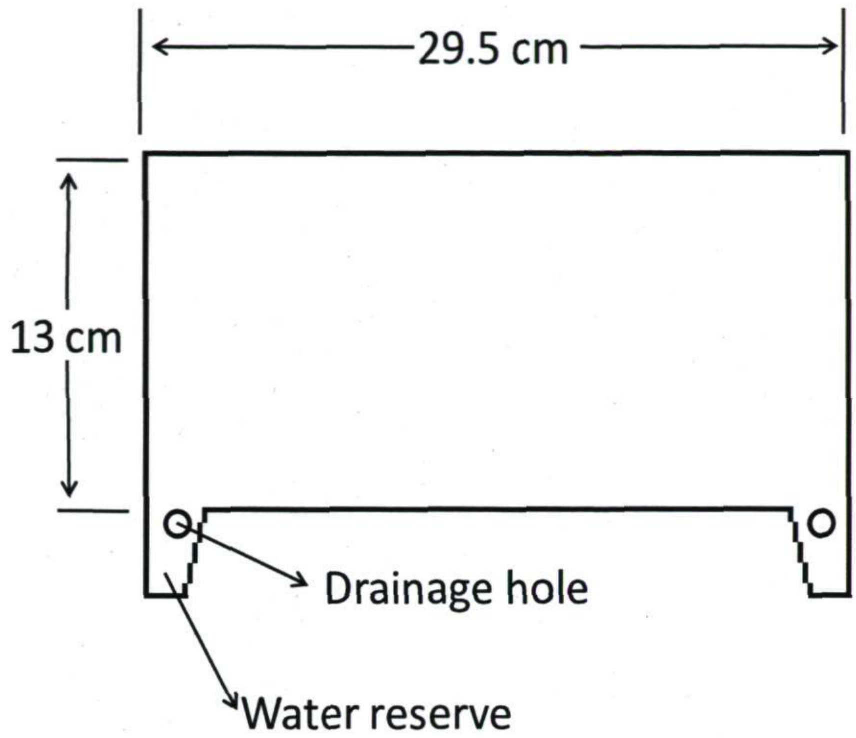

Figure 1 : Scheme of the plastic containers for treatments SP-C and PS-C

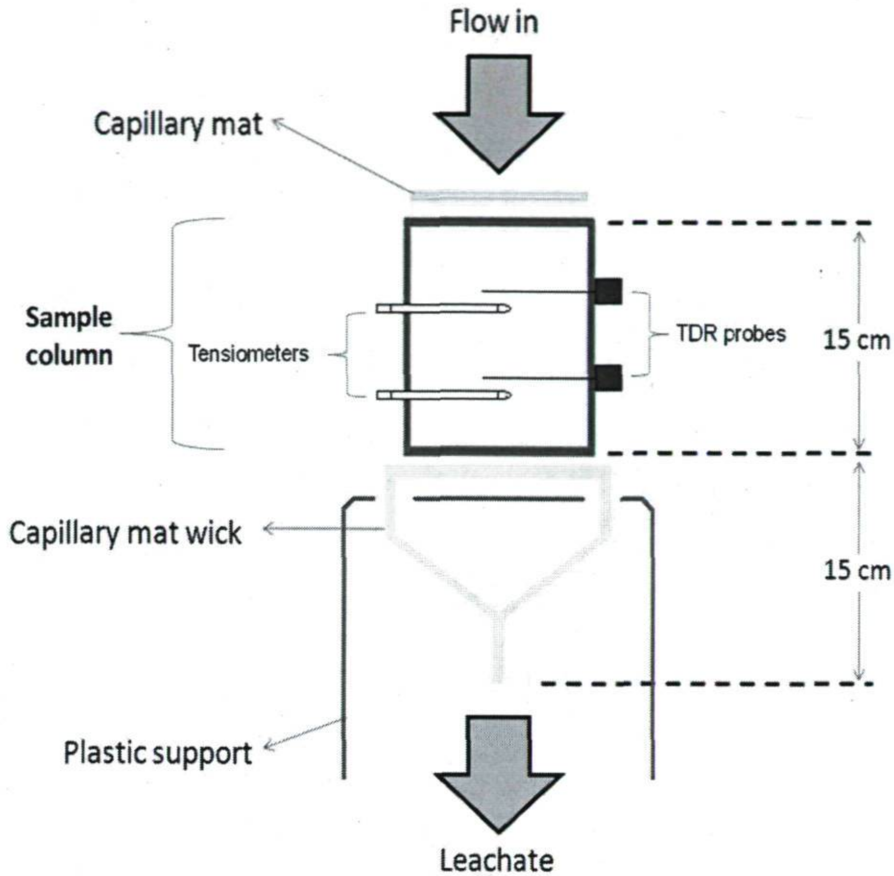

Figure 2 : Experimental setup for the leaching experiment

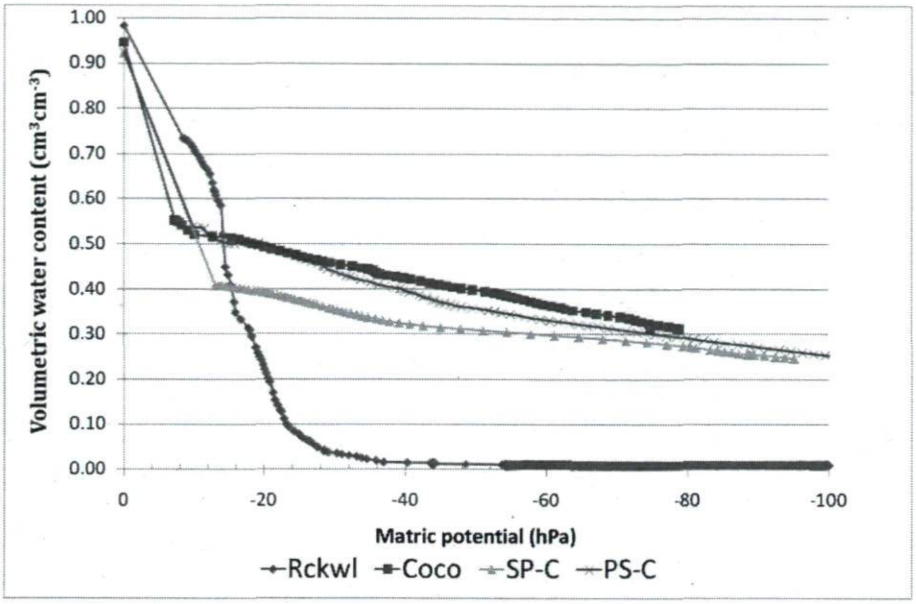

Figure 3 : Water retention curves of the four growing media during the desorption phase

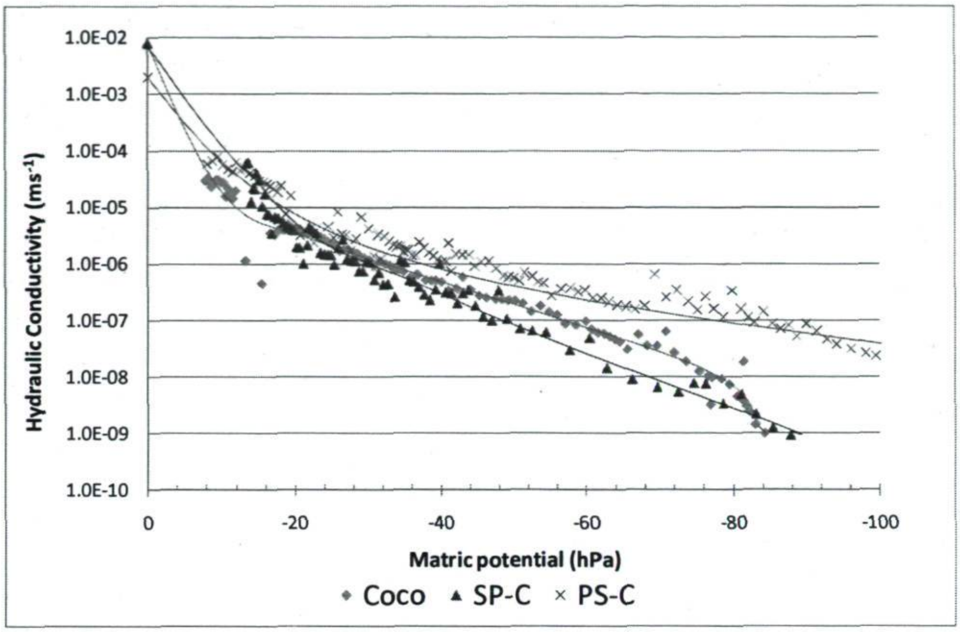

Figure 4 : Unsaturated hydraulic conductivity of the growing media during the desorption phase

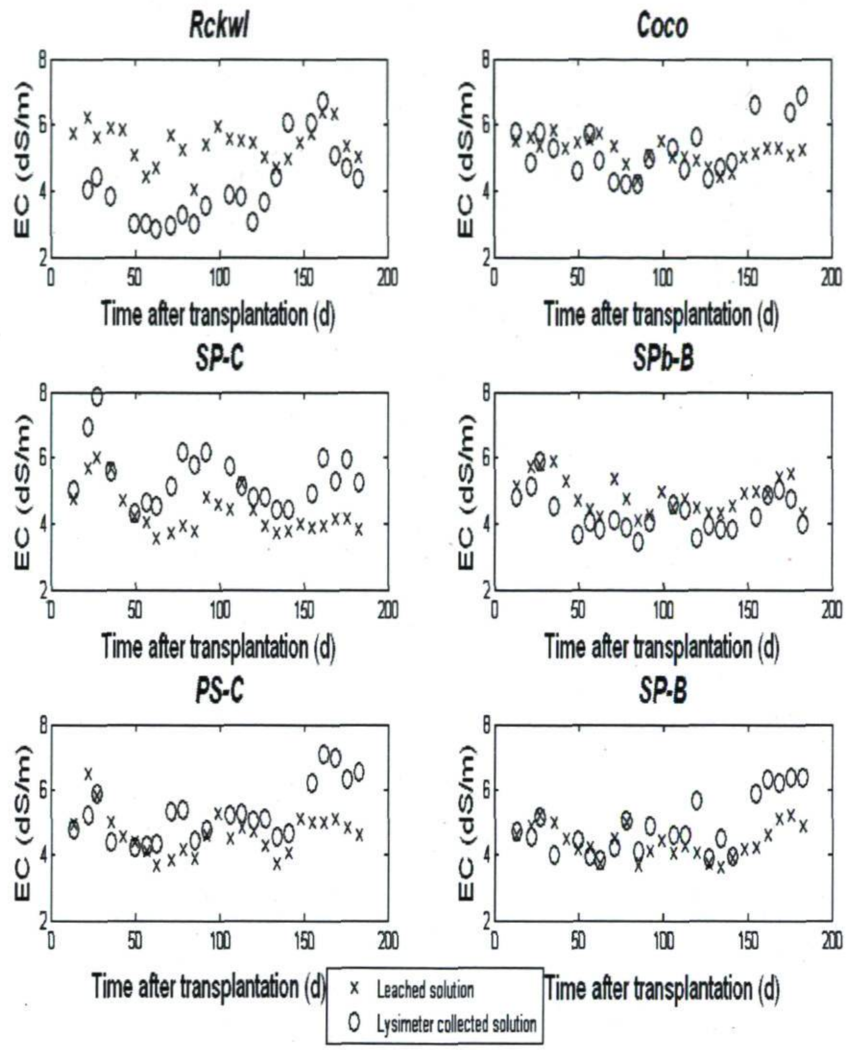

Figure 5 : Comparison of Electrical Conductivity measurements in the soil solution and in the leached solution

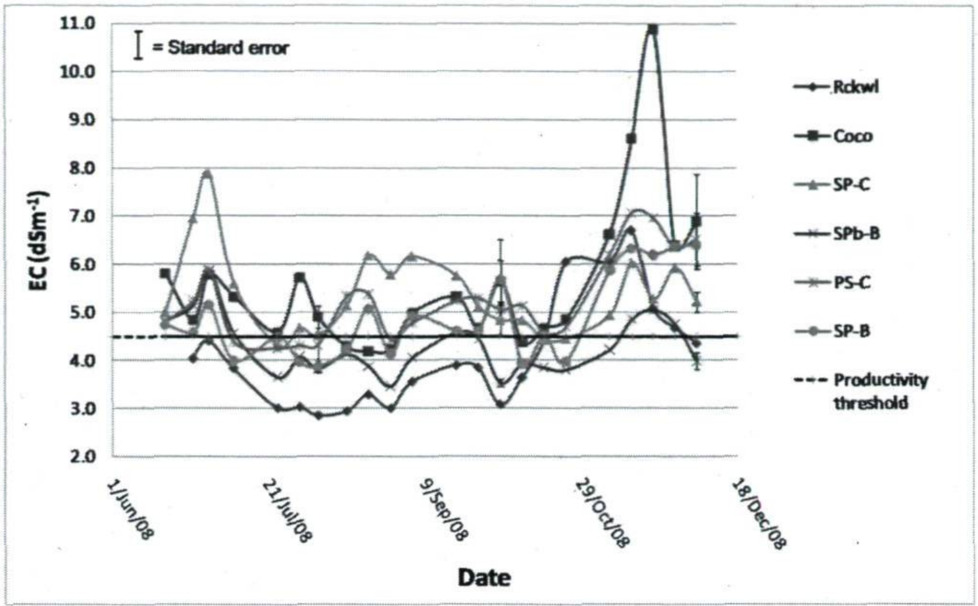

Figure 6 : Evolution of salinity in the soil solution extracted at –6.0 kPa (easily available water) during the greenhouse production experiment

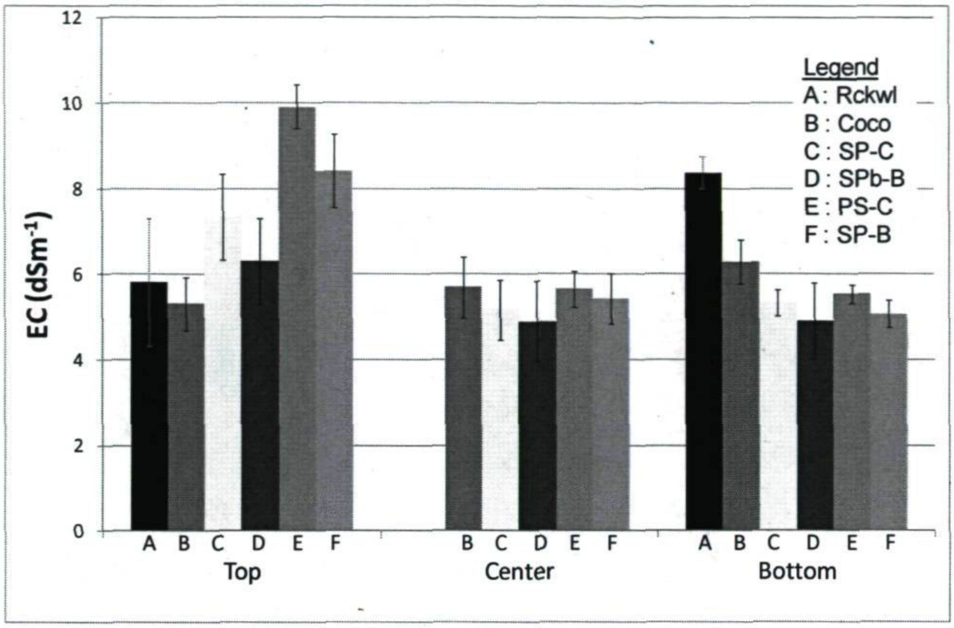

Figure 7 : Electrical conductivity from saturated medium extracts in the growing media at three sampling depths at the end of the production period (mean +/- SE).

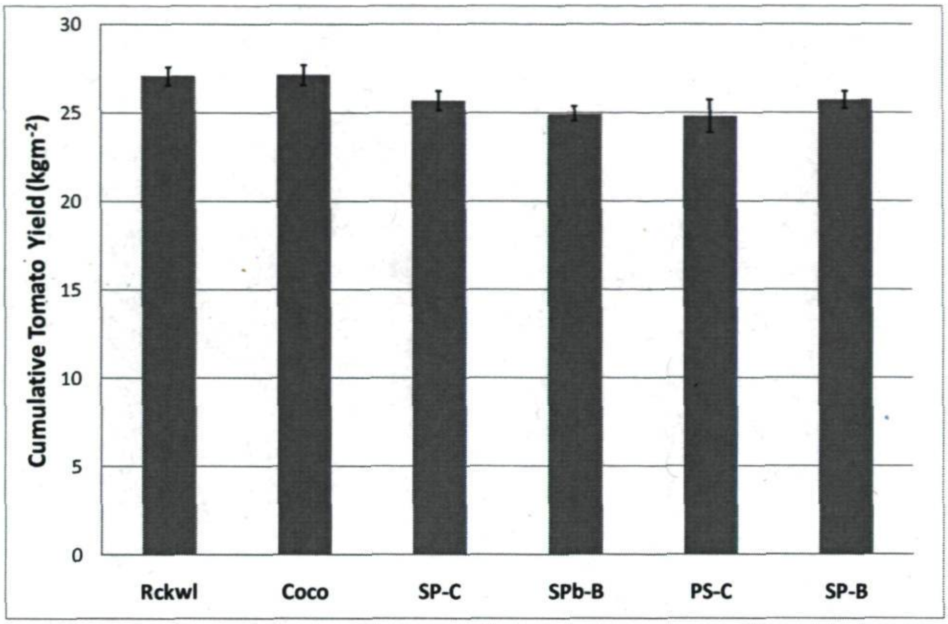

Figure 8 : Cumulative tomato marketable yield at the end of production (mean +/- SE). Fruits were harvested from July 24th to December 11th, 2008.

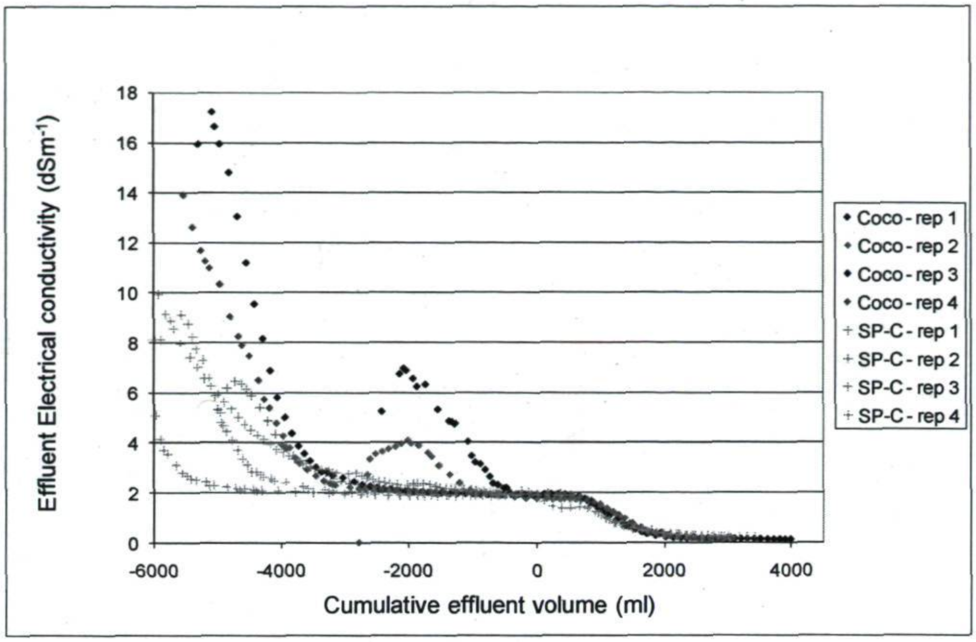

Figure 9 : Solute breakthrough curves during leaching with a nutrient solution (values < 0 on x-axis) and with distilled water (values > 0 on x-axis) for *SP-C* (+) and *Coco* (◊).

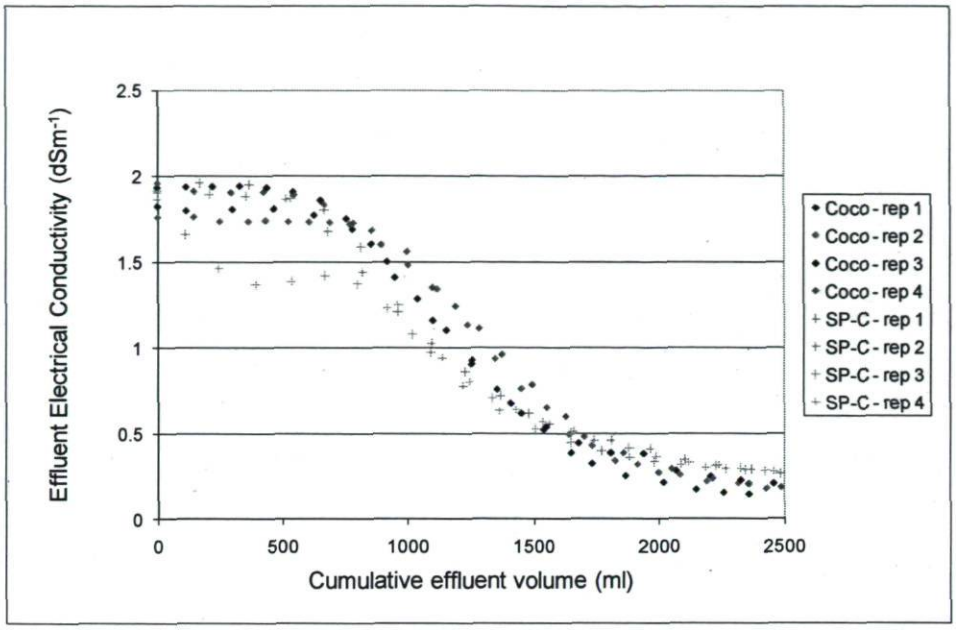

Figure 10 : Close-up of solute breakthrough curves during the leaching with distilled water phase

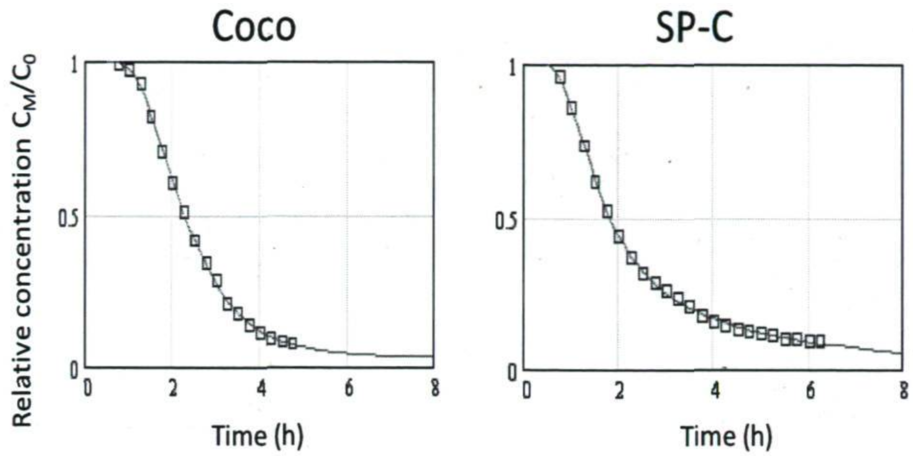

Figure 11 : Examples of fittings of the experimental data sets with the analytical solution to the MIM for *Coco* and *SP-C*. In this case data sets from replicate 1 are shown.

Table 1 : Description of the treatments (composition and container type)

Identification	Composition	container type
Rckwl	Rockwool	13.5 l slab
Coco	Coconut fiber	17.8 l slab
SP-C	30% peat - 70% sawdust	13 l container
SPb-B	30% peat - 70% sawdust with microbial agent	13 l supported bag
PS-C	70% peat - 30% sawdust	13 l container
SP-B	30% peat - 70% sawdust	13 l supported bag

Table 2 : Composition of the nutrient solution used in experiment B

Element	**N**	**P**	**K**	**Ca**	**Mg**	**SO_4**	**Cl**	**Na**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Mo**
Concentration (ppm)	350	50	584	348	80	370	60	0	3.86	1.61	0.65	0.07	1.32	0.07

Table 3 : Physical Properties of the Growing Media

Treatment	θ_S ($cm^3_w\,cm^{-3}_{blk}$)	θ_{CC} ($cm^3_w\,cm^{-3}_{blk}$)	K_{SAT} (ms^{-1})	AP ($cm^3_{air}\,cm^{-3}_{blk}$)	EAW ($cm^3_w\,cm^{-3}_{blk}$)	ρ_A ($g_{soil}cm^{-3}_{blk}$)	ρ_S ($g_{soil}cm^{-3}_{blk}$)
Rckwl	**0.98 a**	**0.76 a**	0.0061 ab	**0.22 c**	**0.73 a**	0.08 c	2.65 a†
Coco	0.94 b	0.59 b	0.0051 b	0.35 b	0.21 b	0.09 bc	1.43 a
SP-C	**0.92 c**	**0.44 c**	0.0086 a	**0.49 a**	**0.11 c**	0.11 ab	1.52 a
PS-C	0.93 bc	0.57 b	**0.0020 c**	0.36 b	0.23 b	0.12 a	1.54 a
LSD	0.013	0.0488	0.0027	0.0513	0.0858	0.0294	1.22

(θ_s = saturated volumetric water content, θ_{cc} = volumetric water content at container capacity, K_{sat} = saturated hydraulic conductivity, AP = air filled porosity, EAW = easily available water, ρ_A = apparent bulk density, ρ_S = real density)

Note : Treatments with the same letter are not significantly different ($P > 0.05$) according to a protected LSD multiple comparison test.
† : For rockwool a theoretical value (2.65 g/cm^3) was used

Table 4 : Statistical analysis of the effects of Medium Compostion and Sampling Depth on the electrical conductivity from SSE extracts.

a) ANOVA

Source	**d.f**	**F**	***P***
Rep	2	1.44	0.2815
Medium Composition (MC)	5	1.07	0.4327
Error A	10	4.08	0.0029**
Sampling Depth (SD)	2	17.19	**<0.0001****
SD x MC	9	8.16	**<0.0001****
Error B	22		

SCE(A) = 30.97

SCE(B) = 16.71

b) Simple main effect contrasts on the SD x MC interaction divided by MC

Source	**d.f**	**F**	***P***
Rckwl	1	12.94	**0.0016****
Coco	2	0.96	0.3972
SP-C	2	5.81	**0.0094****
SPb-B	2	2.62	0.0956
PS-C	2	24.66	**<0.0001****
SP-B	2	13.4	**0.0002****

Table 5 : Average values of the fitted MIM transport parameters for coco and SPb-B during leaching with distilled water. These parameters correspond to conditions observed at the end of the production period.

Substrate	**D**	**V**	**α**	**θ**	**θ_{im}/θ**
---	(cm^2h^{-1})	(cmh^{-1})	(h^{-1})	($cm^3{}_w cm^{-3}{}_s$)	(%)
Coco	5.766 a	5.718 a	0.037 a	0.68 a	**0.195 b**
SPb-B	11.82 a	8.963 a	0.079 a	0.699 a	**0.526 a**
P	0.1372	0.0905	0.4002	0.1696	**0.0243***
LSD	9.5585	4.1901	0.1345	0.0327	0.2502

Note : Values with the same letter are not significantly different (p>0.05) according to a LSD multiple comparison test.

CHAPITRE 3 : PHYSICO-CHEMICAL CONTROL OF THE IMMOBILE PHASE IN PEAT BASED SUBSTRATES DURING SOLUTE TRANSPORT

RÉSUMÉ

L'optimisation de l'irrigation dans les productions en serre peut mener à des rendements supérieurs et une efficacité accrue d'utilisation d'eau et de fertilisants. Les substrats à base de tourbe ont déjà montré leur potentiel pour la culture de la tomate, mais des problèmes d'accumulation de sels y ont été observés. L'objectif de cette étude était de mieux comprendre les processus impliqués dans le transport de soluté en milieux tourbeux. Deux expériences de lessivage en régime permanent ont été réalisées avec cinq substrats (laine de roche, fibre de coco, sable, et deux différents mélanges de sciures et de tourbe). Les courbes de fuite générées par ces expériences ont été optimisées avec une solution analytique du modèle mobile-immobile de transport de solutés (MIM) afin de déterminer différents paramètres de transport, dont la teneur en eau immobile et le coefficient d'échange de masse entre les phases mobile et immobile. Les résultats suggèrent que la phase immobile est contrôlée de manière physico-chimique par la présence de substances humiques.

ABSTRACT

The optimization of irrigation in greenhouse productions can lead to higher yield and a more efficient water and fertilizer use, which can help to diminish the environmental impacts of such productions. Peat based growing media have proven efficient for tomato production but some problems concerning salt accumulation in the substrate have been pointed out. The objective of this study was to investigate the processes controlling solute transport in peat and sawdust substrates. Two steady state leaching experiments were conducted on five media (Sand, Rockwool, Coconut fiber, and two different mixtures of peat and sawdust) in order to generate solute breakthrough curves (BTC). The BTCs were then fitted with an analytical solution to the mobile-immobile transport model (MIM) in order to determine estimate MIM parameters including the immobile water fraction (θ_{im}/θ) and the mass exchange coefficient between the mobile and immobile phases (α). The results suggested that the immobile phase may be controlled physico-chemically by humic substances.

INTRODUCTION

With increasing pressure to improve productivity, many fruit/vegetables and ornamentals producers have gone from soil to soilless production systems. Doing so, cucumber, tomato and pepper greenhouse productions have, in the last decades, undergone considerable expansion. The same pattern is nowadays being followed by strawberry and raspberry producers. In soilless systems, salt accumulation in the growing media is a frequently acquainted problem. While thoroughly studied in soil science, solute transport in growing media is limited to applied studies with little awareness of the underlying mechanisms. These mechanisms are important to identify in order to adequately design substrates and to apply proper irrigation management, leading to productivity improvements and a better water and nutrient use efficiency.

Peat based growing media in horticulture

In North America and Europe, 95% of greenhouse production is realized hydroponically on artificial growing media (Peet and Welles, 2005). Rockwool is the most popular of these artificial media, being used by 80% of Canadian production sites (Carrier, 1999). It is known to provide high yields, but it has three major disadvantages. First its production is realized by high temperature melting of coal, limestone and gypsum, which requires a lot of energy (Scettrini and Jelmini, 2004). Secondly, it is not biodegradable and due to its low density it tends to shorten the useful life of landfills (Allaire et al., 2005). Finally, its use generally leads to high water and fertilizer inputs and leaching.

Another popular substrate is coconut fiber. Like rockwool, it provides high yields and it has the advantage of being biodegradable. Its main inconvenient is its high cost which is due to the fact that coconut fiber production is realized overseas, mainly in Sri-Lanka. Its transportation to Europe and North America also leads to greenhouse gases emissions.

Recently, the use of alternate growing media composed of screened white spruce sawdust and moderately decomposed brown peat (H4-H5 on the Von Post scale) have

been investigated in greenhouse tomato production experiments. White spruce sawdust is a byproduct of the forest industry and is easily available at low prices on a local scale (Dorais, 2003). The use of peat in horticultural substrates is being questioned in Europe and North America because of the environnemental issues associated with peatlands exploitation. Nevertheless, brown peat, because of its physical properties, is not as popular as blond peat for horticultural purposes and its use can lead to a rationalized exploitation of already existing peatlands (Allaire et al.,2005). Many studies report that these environmentally sound peat-sawdust substrates have proper physical properties for greenhouse tomato production and can provide yields comparable to rockwool and coconut fiber (Lemay, 2006; Juneau et al., 2006; Létourneau, 2010; Allaire et al., 1996; Allaire et al., 2005; Bégin, 2008).

Some studies have reported salt accumulation problems in peat based growing media during tomato production (Létourneau, 2010; Lemay, 2006). Studies suggest that salt accumulation is influenced by the electrical conductivity of the fertilizer solution, the irrigation application frequency and the leaching fraction of irrigation solution (Blanco and Folegatti, 2002; Badr and Taalab, 2007). The effects of salinity on tomato plants are well documented. Xu et al. (1995) demonstrated that salinity and water stresses diminish the plants' photosynthetic activity and leaf water potential. Sonneveld and Kreij (1999) showed the importance of root zone salinity on plant water and nutrient uptake and yield quality and quantity. Cuartero and Fernandez-Munoz (1999) also report negative impacts of high substrate salinity for all growing stages of tomato plants.

Properties of peat

Peat is widely used as growing medium in greenhouses and nurseries but little is known about solute transport in that medium (Baird and Gaffney, 2000). Large scale investigations have been made on transport parameters in peatlands and polders (eg. Kennedy and Price, 2004; de Vos et al, 2002), but fewer studies have been conducted on small scale solute transport in peat based growing media.

Some studies suggest that peat has a dual porosity matrix (Loxham, 1980). Some of its pores are poorly connected, closed or dead-end and thus do not show the same water and solute transport properties that larger interconnected pores. Closed pores were observed to act as a sink for solute and induce retardation in solute breakthrough curves (Hoag and Price, 1997). Large tortuosity and poor pore connection have also been observed in peat based growing media by Caron and Nkongolo (2004). This retardation, expressed by asymmetry and tailing of solute in breakthrough curves has also been reported to occur in peat based growing media and coconut fiber samples that had been used in a long term tomato production (Létourneau, 2010). Other studies in mineral soils such as sands, loams or clays have reported early breakthrough and tailing of chemicals similar to those observed in peat (eg. Clothier et al., 1992; Clothier et al., 1995; Mayer, 2008; Casey et al., 1998). This behavior is often referred to as physical nonequilibrium, defined by Khöne et al. (2004) as short scale discrepancies in flow velocities, pressure heads, water contents and solute concentrations. Physical non equilibrium in mineral soil is generally attributed to preferential flow in large pores and solute retardation in closed or dead-end pores (Coats and Smith, 1964; Jaynes et al., 1995). Some authors have suggested that physical nonequilibrium would occur in peat (Hoag and Price, 1997; Ours et al., 1997) but its importance still needs to be better understood and quantified. Other properties of peat such as water repellency (Dekker and Ritsema, 1996) and hysteresis in the water retention curves (Naasz et al, 2005; Naasz et al., 2008) would also have an effect on water and solute flow through this medium.

Peat is also known for the chemical reactions between organic compounds generated microbial activity and solutes in the aqueous phase. These reactions have also been pointed out to be responsible for solute retardation in peat. Results obtained by Ours et al. (1997) suggest that interactions between solutes and organic-acid functional groups could influence pore size distribution in peat and be partly responsible for the dual-porosity type comportment of peat in solute transport. Ours et al. (1997) also observed that the effects of interactions between solutes and organic functional groups diminished greatly as peat samples were leached repeatedly with solutes and distilled water. The temporal variability of peat's chemical properties is supported by other studies which report the

high mobility of humate colloids, one of the main organic compound present in peat (Cook West, 1990), or the structural changes that occur in humic acids when in contact with a solution with a important ionic strength (Conte and Piccolo, 1999). Differences in adsorption isotherms of peat and peat based substrates, in function of solute application techniques (dynamic vs static) were also reported by Boudreau et al. (2009), supporting the physical non equilibrium concept.

In peat based growing media, the relative importance of physical nonequilibrium and chemical reactions between organic compounds and solutes is poorly understood.

Mobile-immobile solute transport model

The mobile-immobile model (MIM) developed for petroleum engineering applications by Coats and Smith (1964) and applied to soil physics by van Genuchten and Wierenga (1977) has frequently been used in the past few decades to describe solute transport in porous media in which physical nonequilibrium was observed, in both laboratory and field scale studies. This conceptual model implies that a medium's volumetric water content (θ) can be divided in a mobile (θ_m) and an immobile region (θ_{im}), with $\theta = \theta_m + \theta_{im}$. It states that in the mobile region, Darcian flow occurs and solute is transported by advective and diffusive processes, while in the immobile region, water has no velocity and solute transport is possible only by diffusion. According to the model, the transport of a conservative solute for a 1D steady-state flow can be expressed

$$\theta_m \frac{\delta C_m}{\delta t} + \theta_{im} \frac{\delta C_{im}}{\delta t} = \theta_m D_m \frac{\partial^2 C_m}{\partial z^2} - q \frac{\delta C_m}{\delta z} \qquad [1]$$

where θ_m and θ_{im} [L^3L^{-3}] are the mobile and immobile volumetric water contents, C_m and C_{im} [ML^{-3}] are the solute concentrations in the mobile and immobile regions, D_m [L^2T^{-1}] is the hydrodynamic dispersion coefficient, t [T] is time and z [L] is depth, q [LT^{-1}] is the Darcian water flux density and can also be expressed as

$$q = v\theta_m \qquad [1.1]$$

where v is the pore water velocity (LT^{-1}). Exchange between the mobile and immobile regions can be written

$$\theta_{im}\frac{\delta C_{im}}{\delta t} = \alpha(C_m - C_{im}) \qquad [2]$$

where α [T^{-1}] is a first order mass exchange coefficient between the mobile and immobile regions. In a case where there is no immobile water ($\theta_{im}= 0$), eq. [1] can be reduced to the conventional convection-dispersion equation (CDE) which is commonly used to describe solute transport in all kinds of porous media.

Since the mid nineties, many research efforts have been attributed to the estimation of MIM parameters in both field and laboratory experiments. Tracer experiments using tension infiltrometers proposed by Clothier et al (1992) and developed by Jaynes et al (1995) have been used and tested by many research groups (Lee et al, 2000; Lee et al, 2002; Casey et al, 1998; Alleto et al., 2006; Al-Jabri et al., 2002), providing reasonable estimates of θ_{im} and α. The validity domains for the assumptions of these tracer methods have been defined mainly in relation with soil dispersivity (Snow, 1999).

Other satisfying results were provided by inverse modeling of solute breakthrough curves (BTCs) with analytical or semi-analytical solutions to the MIM. Solute concentrations calculated from time domain reflectometry (TDR) measurements of impedance load (Lee et al., 2000) or directly obtained from electrical conductivity measurements of effluents (Mayer et al., 2008; Khöne et al., 2004) were used to generate the experimental BTCs.

Most of these estimations of MIM parameters were conducted on sandy or loamy soils with low organic matter content and thus cannot be used to describe transport phenomena in peat based media. The objectives of this study are to investigate the presence of an

immobile water phase in different peat based growing media and to estimate MIM parameters (θ_{im}, α, D_m, v) for three type of growing media and a reference material.

MATERIALS AND METHODS

Experiment A

Experimental design

In order to obtain a better understanding of the causes and effects of salt accumulation in organic growing media, an experimental procedure in which salt accumulation was artificially induced was designed. The ease at which salt levels were brought back to initial levels through a leaching process was then evaluated. The effect of two types of salt accumulation processes (main plot) and of four media composition (sub-plot) on MIM transport parameters were evaluated in a split-plot design with three replicates.

In order to verify if the media's pore size distribution was influenced by solute concentration, the variation in saturated hydraulic conductivity measured prior and after the leaching process was evaluated. In this case a split-split-plot experimental design with the leaching effect in main plot, and the saturation and medium composition respectively in sub-plot and sub-sub-plot was designed. In both cases, analyses of variance (ANOVA) were carried out on the results with the SAS ver 9.1 software (SAS institute, Cary, NC). When main effects prove significant, simple contrast test were performed and in the event of a significant interaction, simple main effect contrasts were performed. The experiments were carried from September to December 2008.

Growing media

Three organic growing media and one reference material were studied in this experiment. Two different mixtures of peat with a degree of decomposition of H4-H5 on the Von Post scale and white spruce (*Picea glauca*) sawdust (Premier Horticulture Ltée, Riv.-Du-Loup, Qc, Can) were used. Volumetric proportion of peat and sawdust were 30:70 in the

first mixture (*SP*) and 70:30 in the second one (*PS*). For both treatments, sawdust particles size ranged between 2 and 6 mm and pH was adjusted to 5.5 by adding fine calcitic lime. The name of the mixtures refers to their air filled porosity at hydrodynamic equilibrium after free drainage. The other organic medium at use (*Coco*) was a commercial coconut coir slab (Biogrow duo, Groupe Horticole Ledoux, Qc, Can). Finally, an all use sieved construction sand (Sable Marco inc., Canada) was used as a reference material (*Sand*). A summary of the main physical properties of the four treatments is presented in Table 1.

Six polyvinyl Cl (PVC) cylinders (150 mm height and 133 mm internal diameter) of each material were manually packed for a total of 24 cylinders. A wire netting with a 1.0 mm mesh was fixed at the lower boundary of the cylinders to prevent material loss. Cylinders were perforated on one side with two 10-mm diam. holes at respectively 30 and 90 mm from the bottom to allow further the insertion of tensiometers. On the other side of the cylinder, two series of three horizontally aligned holes (2-mm diam.; 15 mm spacing) were perforated at 50 and 100 mm from bottom for the insertion of TDR probes. For the treatments *SP* and *PS* and Sand, the material was slightly hydrated with distilled water and poured into the cylinders to the top limit. The cylinders were then dropped three times from a 10 cm height onto a hard horizontal surface. The space made available on the top part of the cylinders due to material compaction was then filled with loose material. For the Coco treatment, a 133-mm diam. disc was cut from a dehydrated coconut coir slab and put into a cylinder. It was then slowly hydrated from the bottom with distilled water causing the material to expand to a height between 125 and 135 mm. Available space on top of the cylinder was filled with independently humidified loose material. For all treatments, this procedure well mimicked the medium bulk density in greenhouse conditions at the beginning of production.

Saturation treatments

In order to provoke salt accumulation within the media, two treatments of saturation (SS: Short Saturation and LS: Long Saturation) with a saline solution were randomly applied

to the sample cylinders. In fact, all cylinders were submitted to a sequence of three cycles of a full, slow saturation from the bottom and then free drainage. Cycles 1, 2 and 3 lasted respectively 24h, 21 days and 24h. The cycle duration was defined as the time during which the cylinders rested in the saturation solution. For both treatments, the saturation solution was distilled water during cycle 1 and a NaCl solution during cycle 3. The difference between the SS and LS treatments was that during cycle 2, distilled water was used as the saturation solution for the SS treatment while NaCl solution was used for the LS treatment. The NaCl solution's electrical conductivity was adjusted to 2.2 dSm^{-1} in all cases. The distilled water and NaCl solutions were maintained at ambient room temperature of 23°C during all the procedures.

Saturated hydraulic conductivity

At the end of the saturation cycles, the cylinders were put in an apparatus (Figure 1) that allowed the measurement of the medium's saturated hydraulic conductivity with the Constant Head Method described in Reynolds (2008). This method implies the measurement of the flow rate Q $[L^3T^{-1}]$ that is required to maintain the hydraulic head ΔH [L] constant over the whole medium area S $[L^2]$ as water flows through a known medium length L [L]. The saturated hydraulic conductivity K_{sat} $[LT^{-1}]$ is then calculated with Darcy' Law for steady-state flow through a porous medium :

$$Q = -K_{sat}\frac{\partial H}{\partial L} \rightarrow -K_{sat}\frac{\Delta \mathrm{H}}{\Delta \mathrm{L}} \qquad [3]$$

The particularity of the method in this case was that before the leaching experiment, the K_{sat} was measured with only a NaCl solution in the system and after the leaching experiment, only distilled water was used. NaCl solution was of same composition that the one used during the saturation process. The difference between the two measured values was then calculated and statistically analyzed.

Leaching experiment

Immediately after the K_{sat} measurements with the NaCl solution, substrate cylinders were place on the apparatus shown in Figure 2. The lower part of the cylinder rested on a circular fiberglass capillary mat (thickness : 2.95 mm, diameter : 14.25 cm) which at two opposite ends was prolonged by a 33.94 mm wide wick of the same material. The two wicks extended through holes in the plastic support and were joined together under it, their common extremities being exactly 15 cm under the lower limit of the cylinder. That kind of capillary mat has a high hydraulic conductivity and was proven not to retard solute transport. It played two roles in the apparatus: 1) allowing easy collection of the effluent from the cylinder 2) applying a –1.5 kPa water potential on the lower part of the cylinder. Another capillary mat disk was put over the top of the cylinder to : 1) protect the medium against the impact from solution/water drops coming out of the infiltrometer 2) insure a uniform distribution of the flow in through the cylinder area 3) prevent evaporation losses. The cylinder was also equipped with two horizontally inserted TDR probes (three 12.0 cm long rods of 0.16 mm diameter, with a 12 mm spacing, inserted at 5.0 and 10.0 cm from the bottom of the cylinder) and two tensiometers inserted at 3.0 and 9.0 cm from the bottom of the cylinder, and whose porous cup (15.0 mm long, 10 mm diameter) were placed on its central axis (Figure 2). The equations presented by Caron et al. (2002) were used to convert TDR readings to volumetric water content. All areas exposed to air were covered with plastic film to prevent evaporation losses.

As soon as the cylinder was placed on the apparatus, instrumented and covered, a steady flow (6-8 ml/min) of NaCl solution with an electrical conductivity of 2.2 dSm^{-1} was applied on the top of the cylinder with an infiltrometer which had been modified to provide a steady drip flow through radially disposed hypodermic needles. The magnitude of this flow rate has been selected to represent drip irrigation flow rates in a greenhouse production situation. This flow was applied until steady-state conditions were obtained, which was verified with automated TDR measurements of volumetric water content (TDR100, SDMX50, CR23X, Campbell sci., Cal. USA), measurements of the substrate's matric potential with tensiometers and measurements of the flow rate of the effluent from

the substrate. The steady-state conditions were defined as : 1) constant volumetric water content 2) constant matric potential 3) no difference between inflow from infiltrometer and effluent outflow.

When steady-state conditions were obtained, the inflow was switched from NaCl solution to distilled water, maintaining the same rate of application. From that moment on, effluent from the substrate was collected at fixed intervals of time, and volume and electrical conductivity measurements were made in order to plot breakthrough curves (BTC) of salt movement through the media. The leaching experiment went on until the electrical conductivity of the effluent had stopped decreasing or showed very slow decrease.

Parametric fitting

BTCs from the leaching experiment were fitted with an analytical solution to the MIM developed by Toride et al. (1995) but adapted to experimental conditions using the Mathcad software (Parametric Technology (Canada) Ltd. - Montreal). Time dependent effluent concentration data were fitted for v, D_m, θ/θ_m and α, assuming that experimental data was the concentration in the mobile C_m [ML^{-3}] phase at a 15 cm depth and that the initial mobile concentration C_0 [ML^{-3}] was the concentration of the NaCl solution used for saturation, K_{sat} initial measurements and initial leaching to obtain steady-state. A minimization of the sum of square errors (SSE) between experimental and fitted data procedure was used to improve the accuracy of the results.

Experiment B

Experimental Design

This experiment was designed to evaluate the impact of saturation processes on the further leaching behavior of one of the peat based substrate (*SP*). It was also designed to obtain a better understanding of the behavior of the media during the NaCl application phase of the experiment. This was made possible by the application of a NaCl solution to

the substrate brought to different initial matric potentials, and then by proceeding to the leaching experiment described earlier. Four different saturation treatments were applied to columns of *SP* in a completely randomized plot with four replicates. Analysis of variance (ANOVA) and in some cases simple contrast tests were performed with the SAS ver 9.1 software (SAS institute, Cary, NC). The experiments were carried from June to August 2009.

Saturation treatments

Artificially packed cylinders of the *SP* treatment were prepared as described in experiment A. For the first treatment (ψ_{cc}) the substrate cylinder was slowly saturated from the bottom with distilled water, left to rest for 24h, and allowed to drain freely until hydrodynamic equilibrium (container capacity) was attained. It was then slowly saturated from the bottom with a saline solution and left to rest for 24h. This treatment is similar to the SS treatment of experiment A except that the 21 days saturation-drainage cycle with distilled water was skipped. It was used as a reference treatment.

For two other treatments (ψ_{20} and ψ_{50}) the same saturation-drainage cycle with distilled water than for the ψ_{cc} treatment was repeated, but when container capacity was attained, the cylinders were put onto a tension table. For the ψ_{20} treatment, the matric potential applied (calculated from mid-height of the cylinder) with the table was -20 hPa. The cylinder was left on the table for 48-72 hours until hydrostatic equilibrium was reached. The cylinders were taken out of the tension tables, and an amount of saline solution corresponding to the volume of water lost from by drainage on the tension table was slowly applied to the substrate by aspersion from the top. The same procedure was repeated for the ψ_{50} treatment but the potential applied on the substrate with the table was -50 hPa. Finally, a fourth treatment (ψ_{air}) consisted of rewetting by slow aspersion an air dried sample with saline solution only, from dry state to container capacity. In all cases the saline solution was a NaCl solution with a 2.2 dSm^{-1} electrical conductivity at 23°C.

Leaching and parametric fitting

After the application of the saturation treatments, the procedures of experiment A were realized. Additional EC measurements of the effluent were realized during the NaCl application phase to produce the BTCs of the whole process, but the parametric fittings were performed on data obtained from the leaching with distilled water phase of the experiment only.

Physical properties after leaching

Immediately after the end of the leaching experiment, the substrate cylinders were weighted and oven dried to measure the volumetric water content. The height and area of the growing media were measured with a digital caliper in order to calculate the media's apparent bulk density and total porosity from :

$$\rho_a = \frac{m_{dry}}{V_{bulk}} \quad [4] \qquad \text{and} \qquad P = 1 - \frac{\rho_a}{\rho} \quad [5]$$

Where ρ_a is the apparent bulk density of the substrate [ML^{-3}], ρ is the real density (1.55 g/cm^3 in the case of an organic media) of the substrate [ML^{-3}], m_{dry} is the weight of the oven dried substrate, V_{bulk} is the bulk volume of the substrate [L^3] and P is the total porosity of the substrate [$L^3{}_{air}L^{-3}{}_{bulk}$].

RESULTS AND DISCUSSION

Experiment A

Leaching experiment

For both saturation treatments, experimental BTCs (Figure 3) for sand, *SP* and *PS* had in common a quite symmetrical shape (about the point where the relative concentration was 0.5) and did not show much tailing effect. The main difference between these three treatments was that the volume of distilled water required to reach the first inflection

point on the relative concentration curve, or the point where relative concentration suddenly drops, was higher for the treatments with a larger proportion of peat (*PS>SP>Sand*). The position of that point is closely related to the pore water velocity (v) of water through the medium. Since the experimental flow rate through the media was maintained steady and was very similar for all these treatments, the differences between pore water velocities could be explained by 1) lower mobile water content (θ_m) in *Sand* relative to *SP* and *PS* or 2) higher tortuosity (τ) in the organic media relative to Sand.

It is also noticeable that the rate at which the relative concentration went down was higher for *SP* and *PS* than for *Sand* (Figure 3). That could be explained by a higher hydrodynamic dispersion coefficient (D_m) in *Sand* than in the peat-based media, which was quite unexpected since D_m is closely linked to tortuosity, expected to be higher in peat based media. After that second inflection point, the three treatments behaved similarly.

For the *Coco* treatment, the BTC showed much more tailing than for the other three treatments. The salt concentration started to decrease at about the same point than for the peat based media, but it decreased at a much slower rate and the presence of a second inflection point was less clear. This kind of behavior is typical of a dual-porosity medium. Higher residual concentrations were also observed in *Coco* at the end of the leaching experiment.

For all four treatments, a small increase in solute concentration was seen at the beginning of the BTC where, according to the MIM, but also the CDE models, a plateau is expected. As shown in Figures 3 and 4, this was consistently observed in all replicates for all treatments. That leads to believe that some phenomena not properly described by the MIM happened at that stage. Figure 4 also shows that the consistency of the results for peat-based substrates and Sand was very good. More variation was observed with coco fiber. Results from the LS treatment only are shown in Figure 4, but the same behavior was noticed for the SS treatment.

A comparison of the BTCs obtained after both the saturation treatments (Figure 5) clearly shows that saturation type had no effect on the leaching behavior of all four substrates. To be immersed in a NaCl solution for 22 days (LS) or 1 day (SS) did not seem to induce differences in salt distribution in the media's poral network nor in their leaching behavior. It could mean that an equilibrium between NaCl concentrations on adsorption sites in the medium and saturation solution is attained quite rapidly (within one day) or that first order diffusion alone would not induce solute movement into closed or dead-end pores as stated in the MIM model.

Finally, the analysis of variance based on the results of the K_{sat} measurements (Tables 2 and 3) show that the leaching process and saturation type had no effect on K_{sat}. A significant difference due to the interaction between saturation type and medium composition was observed, and results from simple main effect contrasts show that this effect was significant only in coco fiber. The fact that saturation type gives rise to a significant difference in saturated hydraulic conductivity in the pure *Coco* is consistent with findings from Ours et al. (1997) for pure peat, who suggested chemical dilatation of pores inducing changes in medium's hydraulic conductivity.

Parametric fittings

For the four growing media composition, the experimental data points were fitted with a curve modeling the analytical solution to the MIM (Figure 6). The sum of square errors (SSE) between fitted and experimental points ranged from 1.93 x 10^{-5} to 8.85 x 10^{-3}. The minimal SSE that can be obtained from this fitting procedure is 1 x 10^{-6} with theoretical data sets (Table 4). Calculated values of the number of poral volumes required to reach half of the initial NaCl concentration are also presented in the same table.

The fitted immobile water content ratio (θ_{im}/θ) range from 0.085 $cm^3_{w\_im}cm^{-3}_w$ for *SP* to 0.250 $cm^3_{w\_im}cm^{-3}_w$ for *Coco*. The highest immobile water ratio for the two peat based media was 0.112 $cm^3_{w\_im}cm^{-3}_w$ while a maximal value of 0.165 $cm^3_{w\_im}cm^{-3}_w$ was obtained for *Sand*. Statistical analysis of the results showed no significant differences

between treatments and very low F values for the effects of medium composition, saturation, and their interaction (Table 5). These values are on the low side, but within the range (0.06-0.32 $cm^3_{w\_im}cm^{-3}_w$) reported for sand (Majdoub et al., 2001; Lee et al., 2000).

The same trend was observed for the mass exchange coefficient (α) and the hydrodynamic dispersion coefficient (D_m). Slightly higher values were obtained for *Coco* than the three other treatments but once again, no significant differences were observed. For the pore water velocity (v), no particular trend was observed as values ranged from 4.708 cm/h in *PS* to 7.969 in *Sand*.

The analysis of these results raised at least three possibilities. First, with values of θ_{im}/θ and α lower, but not statistically different in *PS* and *SP* than in *Sand*, it can be inferred that these peat based substrates are not dual-porosity type media. Salt accumulation in these substrates during tomato production would not be a result of physical nonequilibrium, and should therefore be attributed to either chemical processes, uneven leaching from irrigation management in the greenhouse or accumulation of solute resulting from capillary rise at the top surface of the substrate.

Secondly, it is possible that the diffusion of NaCl towards the dead end pores where water is immobile was not achieved by saturation in water followed by drainage to container capacity and wetting from the bottom with NaCl solution. Applied NaCl concentration might have remained within the mobile phase of the media as its mass exchange between mobile and immobile phases (α) might be very close to zero because of the existence of closed pores (Caron and Nkongolo, 2004). This could be explained by the fact that at the moment of the application of the NaCl solution, most of the smaller pores, where physical nonequilibrium is expected to occur, were already filled with distilled water and did not sorb any of the applied NaCl solution through matric potential gradients or surface sorption related processes. These first possibilities are in opposition to conclusions from Loxham (1980), Hoag and Price (1997) and Boudreau et al. (2009)

and previous results from preliminary experiment. Hence, a third explanation was brought to reconcile these apparent inconsistencies.

A close look at the abnormalities of the early stage of the BTC (increase instead of plateau) mentioned earlier leads to this other possible explanation. It can be inferred that the initial K_{sat} measurements with a NaCl solution and the initial leaching of the columns with NaCl to reach steady-state conditions had an effect on the leaching process. It was in fact shown by Ours et al. (1997) that the effect of solute concentration on the hydraulic conductivities (via opening or closing of pores) consistently decreased after consecutive cycles of solute application and leaching with water were applied. Hence, in our case, a leaching of the chemical compounds, most likely humic substances, which are possibly responsible for these nonequilibrium phenomena in peat based media (Ours et al., 1997), might have occurred during the early stages of the experimental procedures. This explanation is supported by the observations made that the effluent solution from the *SP* and *PS* treatments during the drainage phases of the saturation processes and during the initial K_{sat} measurements was observed to be dark brown in appearance, a color typically linked to the presence of humic substances. The effluent color turned lighter in the early stages of the leaching experiment with NaCl and was light yellow colored at the point when leaching with distilled water began. Experiment B helped to identify the underlying mechanisms involved.

Experiment B

Leaching with distilled water

Considering the portion of the breakthrough curves representing the leaching with distilled water phase (positive values on the x axis of Figure 7), no distinction was observed between the four treatments. This part of the curve was indeed very similar to those obtained for the *SP* treatment during experiment A. Neither the early breakthrough nor the tailing can be observed for any treatments, which lead to believe the size of the pores that were available (water free) before the application of a saline solution did not

influence further leaching with distilled water behavior. From that portion of the BTCs, no sign of physical equilibrium was observed for any treatment.

The results of the fitting procedures are shown in Figure 8. Optimized values of MIM parameters fitted to the data points were very similar to what was obtained in experiment A (Table 6). The proportion of immobile water (θ_{im}/θ) obtained for the ψ_{air} treatment (0.194 $cm^3{}_{w\_im}cm^{-3}{}_{w}$) was twice as important as the values obtained for the other three treatments (0.0856-0.103 $cm^3{}_{w\_im}cm^{-3}{}_{w}$) but statistical analysis did not show any significant difference. The highest immobile water proportion in experiment B was still very similar to that obtained for the *Sand* treatment in experiment A. The opposite trend was observed for the exchange coefficient (α) as the lowest value was obtained for the ψ_{air} treatment (0.0219 h^{-1}) as opposed to a maximum value of 0.0733 h^{-1} for the ψ_{20} treatment. Once again no significant difference was obtained for this parameter. No particular trend was observed for the hydrodynamic dispersion coefficient (D) or the pore water velocity (v). These results support the observations from experiment A that no immobile water induced physical nonequilibrium and retardation during leaching with distilled water in peat based substrates.

Earlier leaching with a saline solution

The analysis of the earlier part of the BTCs corresponding to the application on top of the samples of a steady inflow of saline solution until steady-state conditions were attained is different (negative values on the x axis of Figure 7). For the ψ_{50} treatment, the pores initially filled with saline solution were corresponding to matric potentials -10 to -50 hPa. Since it is generally accepted that this range of pores (macropores) are the main contributors to solute transport and since the leaching experiments were conducted at matric potential values ranging from -5 to -10 hPa (from tensiometer measurements, data not shown), it would have been expected to obtain a leachate with the same electrical conductivity (EC) as the input solution as soon as it was applied. As shown in Figure 7, the EC of the leachate was observed to be only 20% of the EC of the input solution. About 1200 ml of saline solution, which represents more than one pore volume for the *SP*

substrate, had to be applied before the EC of the leachate reached the EC of the input solution. Similar observations were made for the ψ_{20} treatment, but the dilution of the input solution was slightly inferior and a more important volume of input solution (1500 ml) was required to reach concentration equilibrium between input solution and leachate.

For the ψ_{cc} treatment, a large proportion of pores (pores sizes corresponding to matric potentials of -10 hPa and above) were already filled with water before the substrate was saturated with saline water. A high initial dilution of the effluent was expected. As shown in Figure 7, the initial salt concentration was observed to represent 50% of the input solution's concentration and an application and 2000 ml of saline solution was necessary to reach concentration equilibrium between input solution and effluent.

For the ψ_{air} treatment, the EC of the effluent was observed to initially represent 140% of the input solution's EC, and equilibrium was reached after the application of 700 to 800 ml of saline solution. Based on visual observations, the color of the effluent was initially darker than for the other three treatments. As leaching progressed, the solution turned lighter and clearer, like for the other treatments. By the time the input solution was switched to distilled water, the appearance of the effluent was the same for the four treatments.

In summary, comparing the ψ_{50}, ψ_{20} and ψ_{cc} treatments lead to the conclusion that the application of a saline solution into small pores allowed distilled water that, presumably, was trapped within closed pores to be released to larger pores and participate to solute transport, causing the observed dilution of the input solution. Alternatively, the applied NaCl, by contracting humic molecules, may have gained access to pores that were previously clogged by humic substances. Distinctions can hardly be made between the ψ_{50} and ψ_{20} treatments, but they clearly differed from the ψ_{cc} treatment.

In the case of the ψ_{air} treatment, no dilution of the input solution was observed because no distilled water was initially present in the medium. EC values of the effluent higher than

the EC of the input solution could be explained by the leaching of organic compounds, most likely humic or fulvic acids, originally present in large pores. It has been demonstrated that concentrated sodium salt can cause removal of humic substances from the soil matrix through surface pH changes or through contraction of their molecular structure (coiling of long chain polymers, charged or uncharged [Conte and Piccolo, 1999]). Indeed, the observed color of the effluent could be explained by the removal of more humic or fulvic substances.

Physical properties after leaching

Gravimetric water content measurements converted on a volumetric basis (θ_{grav}) realized immediately at the end of the leaching experiment were compared in Table 7 with values obtained from TDR measurements at the same moment (θ_{TDR}). Table 7 also shows the values of apparent bulk density (ρ_a) and total porosity (P) which were calculated from θ_{grav} with Eq. [4] and Eq. [5]. As shown in Tables 7 and 8, no significant difference in θ_{grav}, ρ_a and P was observed between any treatments. Considering the effects of the two measurement methods, the four treatments, and their interaction in a split-splot design, the ANOVA presented in Table 9 shows that the effects of measurement method and treatment on the volumetric water content were both significant. Of interest is the fact that the two of the simple main effect contrasts on the interaction between measurement method and treatment were significant in the ψ_{50} and ψ_{air} treatments.

Since there was no effect of the measured θ_{grav} but some with θ_{TDR}, this suggests that the dielectric constant of the growing media was influenced by the treatments. In other words, for a same volume of water (θ_{grav}) present in the medium, more water dipoles had to be oriented during the passage of an electromagnetic signal emitted by the TDR device, as saline solution entered smaller pores. This goes along the previous conclusion from the leaching experiment that the application of a saline solution into small pores allows access to entrapped water, which may be trapped within an open network by high molecular weight polymers of humic substances.

Experiments A and B suggest that, in particular for the *SP* medium, the matric potential of the medium before the application of a saline solution affects further solute transport processes. At higher matric potentials, larger pores are empty, and the applied solution can access smaller pores. That presence of salt in small pores clearly had an effect during the early stages of a subsequent leaching process. It allows the solution (in this case distilled water) initially present in small or maybe closed pores to provide a greater contribution to solute transport (in this case by causing a dilution of the input solution).

Solute transport abnormalities in peat-sawdust mixtures are more likely to be explained by chemical interactions between Na and Cl ions present in the soil solution and organic compounds like humic acids and high molecular weight molecules initially present in the peat-sawdust substrates than by the contribution of hydrocysts, thus supporting the conclusions from Ours et al. (1997). These interactions would affect the medium poral network by increasing pore connectivity and by opening closed pores when polymers covering pore walls openings are coiled and leached out. The measured changes in the substrates' dielectric constant with no changes in volumetric water content support that hypothesis. The possibility to change the chemical conformation of humic acids and eventually leach them out of a substrate, as also reported by Conte and Piccolo (1999) and Cook (1990), could explain the short duration of this chemically induced non equilibrium. This is supported by visual observations suggesting that during the early stages of leaching, humic material is lost from the growing medium. After the leaching of about one pore volume from the medium, the effluent becomes clearer and from that moment on, no more signs of non equilibrium are observed on the solute breakthrough curves. In summary, experiment B confirms the presence of an immobile water phase in the *SP* growing media, this immobile phase being influenced by the presence of salt in small pores, but its effect on solute transport seems to be limited.

CONCLUSION

This study showed that one of the factors explaining salt accumulation in peat based substrates, the presence of an immobile water phase, is closely related to interactions

between the nutrient solution and humic substances present in peat. It has also been pointed out that it is possible to leach these humic substances out of the substrate with a uniform application of a NaCl solution. More experiments are required to obtain a better understanding of salt movements in peat based substrates, but this study suggests that salinity build up is avoidable through optimization of fertigation procedures.

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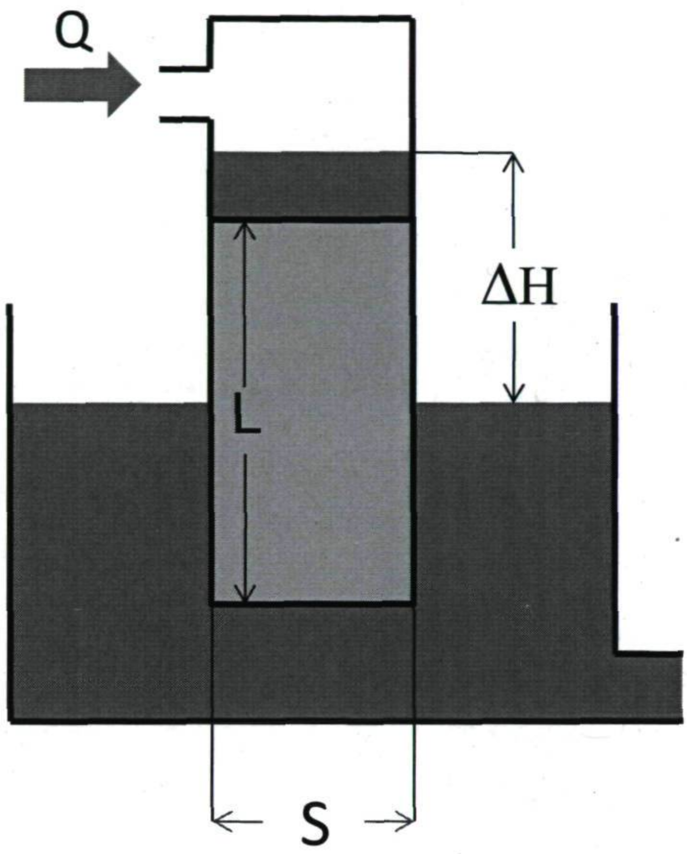

Figure 1 : Apparatus to measure the saturated hydraulic conductivity

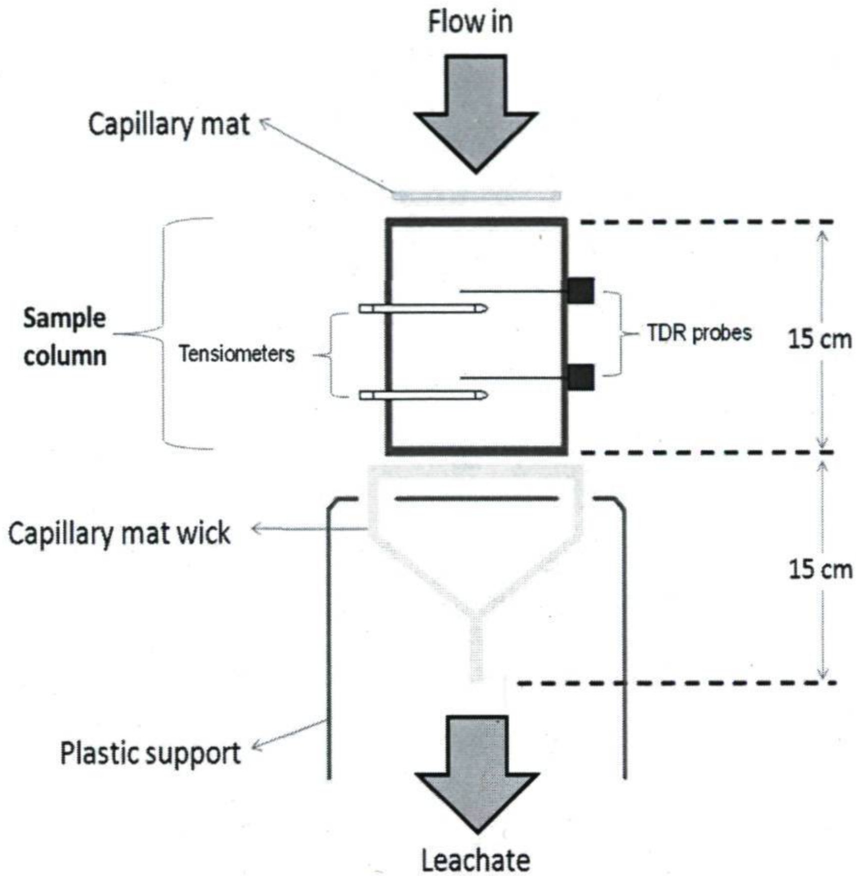

Figure 2 : Experimental setup for the leaching experiment

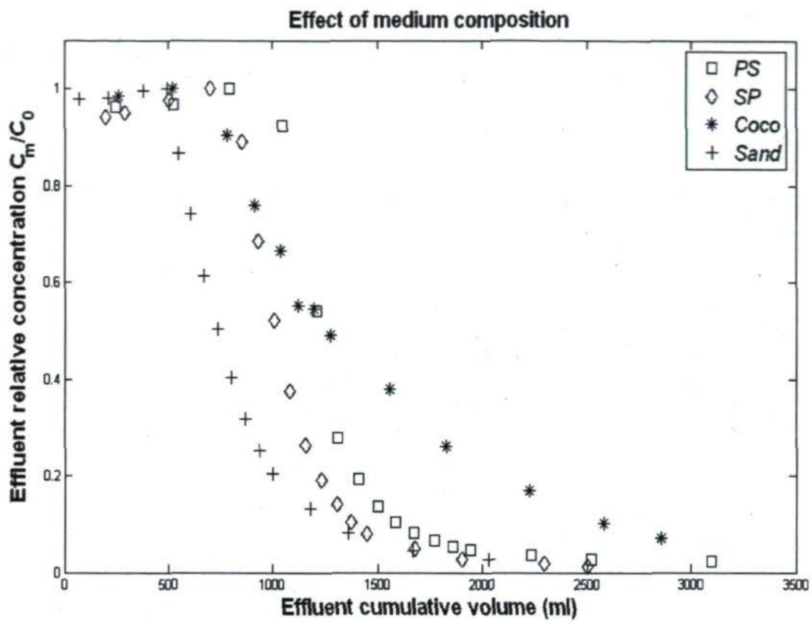

Figure 3 : BTCs for 4 medium compositions during the leaching with distilled water phase

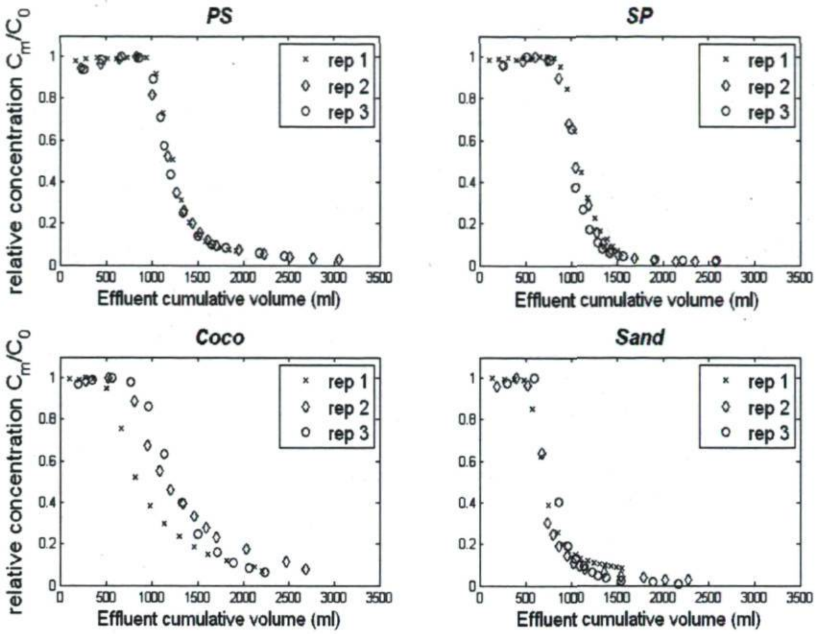

Figure 4 : BTC for 3 replicates of the LS treatment for 4 growing media

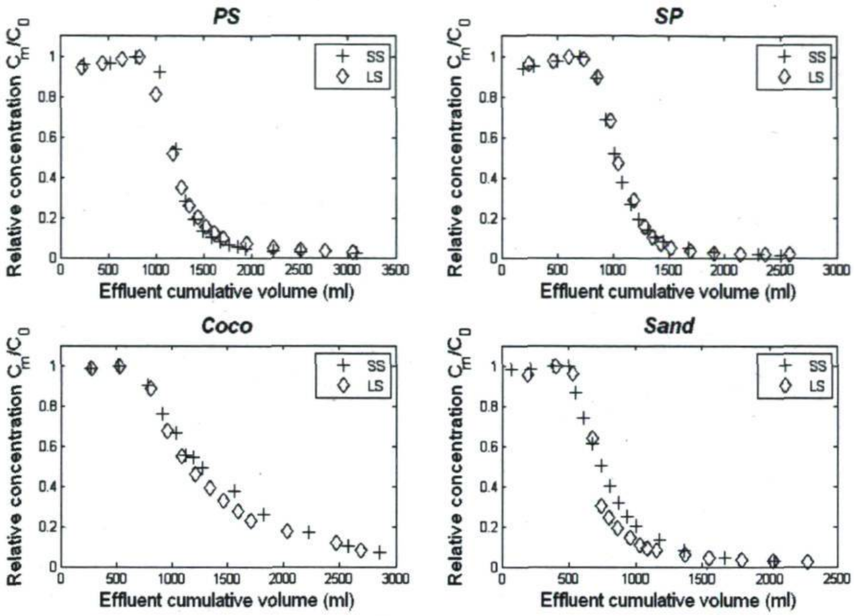

Figure 5 : BTCs for two saturation treatments and 4 substrate compositions (only one replicate is shown)

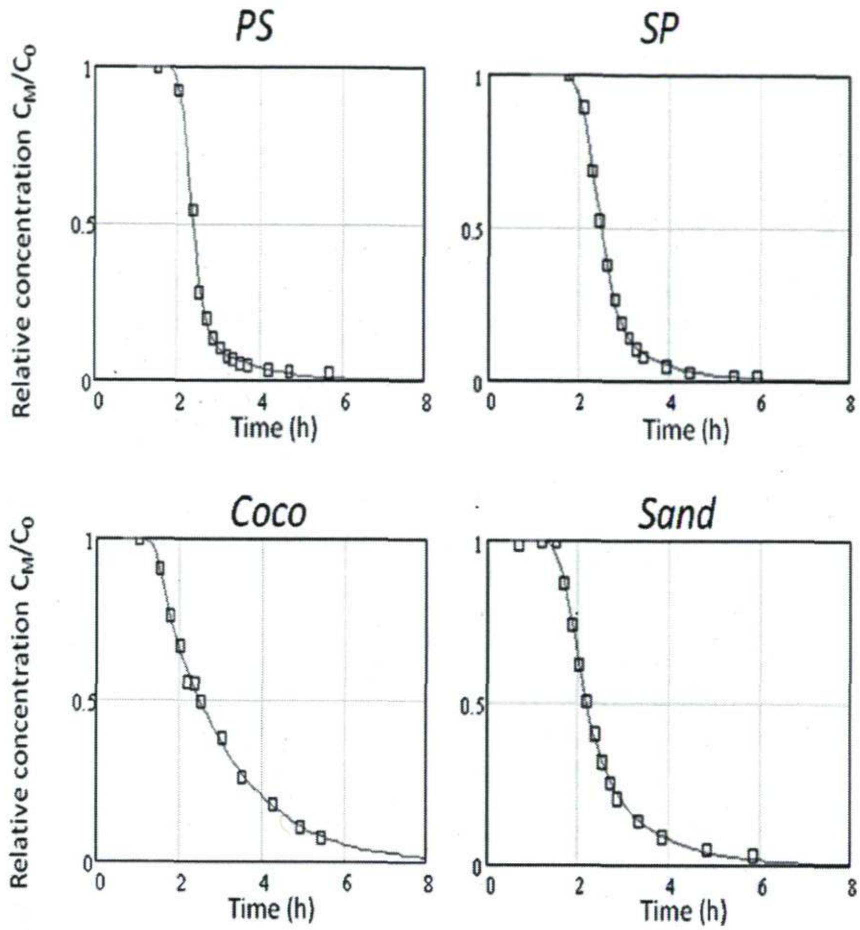

Figure 6 : Parametric fitting of MIM analytical solution to experimental data from experiment A

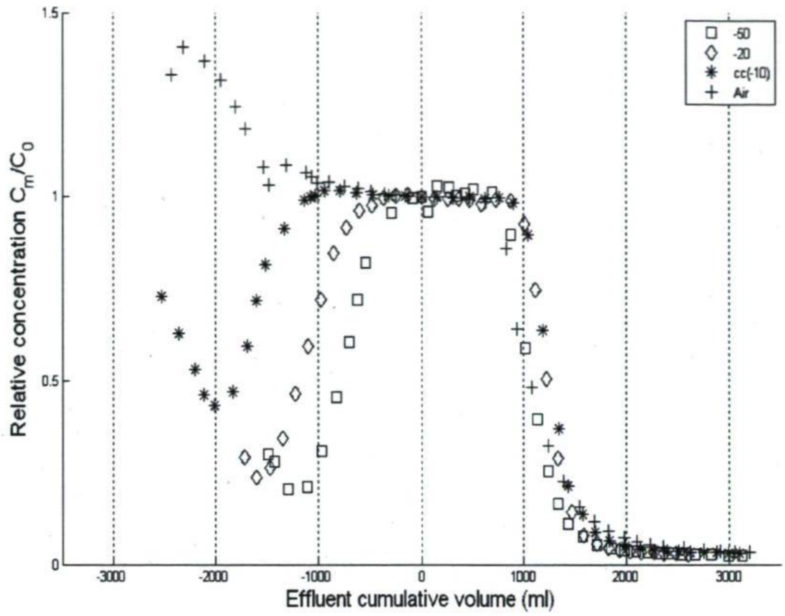

Figure 7 : BTCs for *SP* with 4 saturation treatments. The zero value on the x-axis is the point where input solution was switched from NaCl solution to distilled water

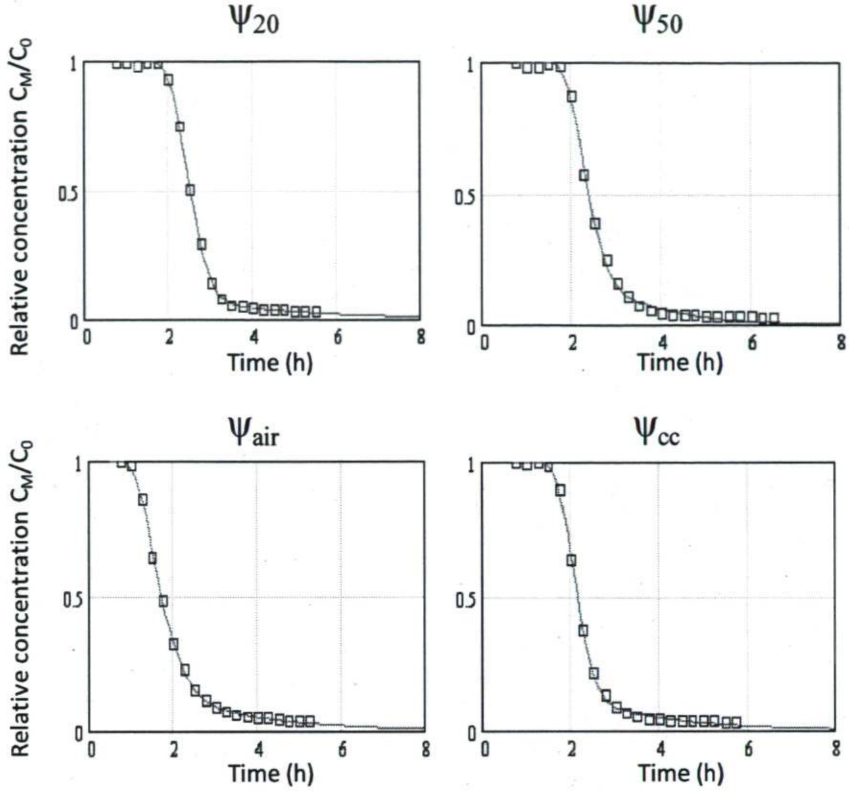

Figure 8 : Parametric fitting of MIM analytical solution to experimental data from experiment B on the *SP* substrate

Table 1: Some physical properties of the organic growing media

Medium	**θ_S** $(cm^3_w cm^{-3}_{blk})$	**θ_{CC}** $(cm^3_w cm^{-3}_{blk})$	**K_{SAT}** (ms^{-1})	**AP** $(cm^3_{air} cm^{-3}_{blk})$	**EAW** $(cm^3_w cm^{-3}_{blk})$	**ρ_A** $(g_{soil} cm^{-3}_{blk})$	**ρ_S** $(g_{soil} cm^{-3}_{blk})$
Coco	0.94	0.59	0.0051	0.35	0.21	0.09	1.43
PS	0.93	0.57	0.0020	0.36	0.23	0.11	1.54
SP	0.92	0.44	0.0086	0.49	0.11	0.12	1.52
Sand	0.34	0.32	0.0027	0.03	0.09	1.53	2.65

(θ_s = saturated volumetric water content, θ_{cc} = volumetric water content at container capacity, K_{sat} = saturated hydraulic conductivity, AP = air filled porosity, EAW = easily available water, ρ_A = apparent bulk density, ρ_S = real density)

Table 2 : Average values of saturated hydraulic conductivities (Ksat) before and after the leaching experiment

	K_{sat} (ms^{-1})							
	PS		*SP*		Coco		Sand	
	Before	After	Before	After	Before	After	Before	After
SS	9.13E-04	1.23E-03	2.68E-03	3.57E-03	1.36E-04	1.29E-04	2.83E-03	2.65E-03
LS	8.64E-04	8.91E-04	3.24E-03	2.84E-03	1.53E-04	2.39E-03	6.11E-03	5.35E-03

Table 3 : Statistical analysis of the effects of leaching (L), saturation (S) and medium composition (C) on the saturated hydraulic conductivity (Ksat)

a) ANOVA on K_{sat}

Source	d.f.	F	p
leaching (L)	1	0.61	0.5164
replicate	2	0.22	0.8172
Error A	2	1.22	0.3154
Saturation (S)	1	2.77	0.1716
S*L	1	0	0.9695
Error B	4	2.86	**0.0476***
Medium Composition (C)	3	26.07	**<0.001****
C*L	3	0.98	0.4199
C*S	3	5.36	**0.0063****
C*S*L	3	1.02	0.4019
Error C	22		

SCE(A) = 2.95×10^{-6}
SCE(B) = 1.39×10^{-5}
SCE(C) = 1.85×10^{-4}

b) Simple Main effect contrasts for the interaction C*S divided by trait for K_{sat}

Source	d.f.	F	p
SP	1	0.02	0.9022
Sand	1	1.9	0.1817
Coco	1	22.02	**0.0001****

c) Simple contrasts for the effect of medium composition on K_{sat}

Source	d.f.	F	p
Sand vs *PS*, *SP* and *Coco*	1	24.22	**<0.0001****
Coco vs *PS* and *SP*	1	32.07	**<0.0001****
PS vs *SP*	1	21.93	**0.0001****

Table 4 : Results of the parametric fittings in experiment A

substrate	saturation	θ_{im}/θ	α	D	V	Pore volumes to reach $C_0/2$	θ
---	--		(h^{-1})	(cm^2h^{-1})	(cmh^{-1})		($cm^3{}_w cm^{-3}{}_s$)
Coco	Short	0.207 a	0.130 a	1.790 a	6.199 a	1.052 b	0.631
Coco	Long	0.250 a	0.128 a	1.379 a	5.707 a	0.947 b	0.606
PS	Short	0.112 a	0.043 a	0.609 a	5.924 a	0.998 b	0.632
PS	Long	0.109 a	0.038 a	0.617 a	4.708 a	0.949 b	0.611
SP	Short	0.104 a	0.063 a	0.565 a	5.657 a	0.986 b	0.567
SP	Long	0.085 a	0.043 a	0.557 a	5.216 a	0.975 b	0.541
Sand	Short	0.162 a	0.046 a	1.486 a	7.969 a	1.131 a	0.346
Sand	Long	0.165 a	0.041 a	0.855 a	7.836 a	1.210 a	0.317
LSD		0.1246	0.0845	0.9833	2.3216	0.1337	NA

Note : Values with the same letter are not significantly ($p > 0.05$) different according to a Least Significant Differences (LSD) multiple comparison test.

Table 5 : Results of ANOVA on fitted parameters for 4 substrate compositions

Effect	d. f.	θ_{im}		θ_{im}/θ		α		D		v	
		F	P	F	P	F	P	F	P	F	P
replicate	2	3.550	0.220	3.890	0.205	2.510	0.285	2.350	0.299	5.170	0.162
saturation	1	0.010	0.923	0.060	0.833	0.130	0.753	7.310	0.114	0.570	0.529
Error A	2	0.270	0.265	0.380	0.691	0.640	0.543	0.090	0.913	1.000	0.396
Medium composition	3	2.700	0.093	2.230	0.137	2.320	0.125	2.330	0.126	2.530	0.106
composition X saturation	3	0.050	0.983	0.110	0.955	0.020	0.996	0.240	0.866	0.090	0.963
Error B	12										
Total	23										
SCE(A)		2.04×10^{-3}		7.46×10^{-3}		5.81×10^{-3}		1.12×10^{-1}		6.83	
SCE(B)		4.45×10^{-2}		1.18×10^{-1}		5.42×10^{-2}		7.33		40.9	

Table 6 : Results of the parametric fittings in experiment B

Treatment	D	V	α	θ_{im}/θ	θ
----	(cm^2h^{-1})	(cmh^{-1})	(h^{-1})		($cm^3_w cm^{-3}_s$)
ψ_{cc}	1.37a	7.20a	0.0473a	0.101a	0.532b
ψ_{20}	0.985a	5.93a	0.0733a	0.103a	0.545b
ψ_{50}	1.50a	6.79a	0.0333a	0.0856a	0.593ab
ψ_{air}	2.72a	6.53a	0.0219a	0.194a	0.610a
LSD	2.7539	2.3043	0.1225	0.1326	0.0667

Note : Values with the same letter are not significantly different ($p > 0.05$) according to a Least Significant Differences (LSD) multiple comparison test. Based on experiments with substrate *SP*.

†Values of θ do not represent fitted values as for D,v,α and θ_{im}, they are experimental measurements

Table 7 : Average values of physical properties of the growing media at the end of the leaching experiment

Treatment	volumetric water content ($cm^3_{water}cm^{-3}_{bulk}$)		apparent density ($g_{soil}cm^{-3}_{bulk}$)	porosity ($cm^3_{air}cm^{-3}_{bulk}$)
	dry weight method	*TDR method*		
ψ_{cc}	0.504a	0.532b	0.126b	0.919a
ψ_{20}	0.523a	0.545b	0.129ab	0.917ab
ψ_{50}	0.510a	0.593ab	0.127b	0.918a
ψ_{air}	0.532a	0.610a	0.136a	0.912b
LSD	0.0391	0.0667	0.0092	0.0064

Note : Values with the same letter are not significantly different ($p>0.05$) according to a Least Significant Differences (LSD) multiple comparison test.

Table 8 : Statistical analysis apparent on bulk density and porosity of the growing media

a) Anova for apparent bulk density

Source	d.f	F	p
Replicate	3	3.41	0.0822
Treatment	3	3.24	0.0904
Error	7		
Total	13		

SCE = 1.54×10^{-4}

b) Anova for total porosity

Source	d.f	F	p
Replicate	2	2.8	0.1186
Treatment	3	2.92	0.1095
Error			
Total	13		

SEC = 7.40×10^{-5}

Table 9 : Statistical analysis on water content of the growing media

a) Anova for volumetric water content

Source	d.f	F	p
Method (M)	1	10.27	**0.0492***
replicate	3	0.58	0.6668
Error A	3	·2	0.1547
Treatment (T)	3	4.72	**0.0152***
M x T	3	2.53	0.0937
Error B	16		
Total	29		

SCE(A) = 5.56×10^{-3}
SCE(B) = 1.46×10^{-2}

b) Simple Contrasts on the effect of Treatment on volumetric water content

Contrast	d.f.	F	p
Air vs Normal	1	12.75	**0.0026****
Normal vs ψ_{20} and ψ_{50}	1	5.12	**0.0378***
ψ_{20} vs ψ_{50}	1	1.34	0.2632

c) Simple main effects contrats for the interraction M x T divided by trait for volumetric water content

Source	d.f.	F	p
ψ_{cc}	1	0.79	0.3882
ψ_{20}	1	1.09	0.3127
ψ_{50}	1	15.21	**0.0013****
ψ_{air}	1	11.88	**0.0033****

CHAPITRE 4 : CONCLUSION GÉNÉRALE

Cette étude s'inscrit dans un contexte où les intervenants du milieu de l'agriculture se doivent de mettre en place et d'améliorer des techniques de production favorisant une utilisation rationnelle des ressources disponibles ainsi qu'un développement durable du secteur des serres. Le développement de substrats de culture permettant la valorisation de sous-produits générés localement, ainsi que l'amélioration des techniques d'irrigation visant à minimiser les demandes en eau et en fertilisants figurent parmi les moyens à la disposition des producteurs serricoles pour réduire leurs impacts environnementaux tout en maintenant des niveaux de productivité élevés. L'objectif principal de cette étude était de faire l'acquisition de connaissances permettant de contrer un problème faisant obstacle à la production avec ce type de substrat, soit l'accumulation de sels dans les milieux de culture. Une expérience de culture en serre de longue durée a été réalisée de manière à comparer différents mélanges de sciures et de tourbe de sphaigne à la laine de roche et à la fibre de coco, tant au niveau des rendements obtenus qu'à celui de l'accumulation des sels en cours de culture. Des expériences en laboratoire ont également été conduites afin de cibler les mécanismes clefs impliqués dans les mouvements de solutés à travers ces substrats.

L'expérience de culture en serre a permis de confirmer la viabilité des mélanges de sciures et de tourbe pour la production de la tomate puisqu'ils ont permis l'obtention de rendements équivalents à la laine de roche et la fibre de coco. Une salinité supérieure, ainsi qu'une différente répartition spatiale des sels ont été observées dans les mélanges sciures-tourbe par rapport à la laine de roche, mais aucun effet négatif de la salinité sur la croissance des plants et la production de fruits n'a été observé.

Cependant, les expériences de laboratoire ont mis en évidence la présence d'une phase d'eau immobile dans les mélanges sciures-tourbe ainsi que dans la fibre de coco. Pour ce dernier substrat, la même proportion d'eau immobile, environ 20%, a été retrouvée en

début et en fin de culture. Pour un des mélanges sciures-tourbe (*SPb-B*), il a été observé que la proportion d'eau immobile passait de 10% en début de culture à 50% en fin de culture. La variation en cours de culture de ce paramètre de transport pourrait être liée à une interaction entre des ions présents dans la solution nutritive et des acides humiques présents dans la tourbe. L'analyse des résultats des trois expériences de lessivage présenté dans cette étude a permis de poser l'hypothèse que les acides humiques présents dans la tourbe jouent un rôle important dans les déplacements de sels en 1) retenant dans leur structure interne eau et soluté et en 2) régissant l'accès de l'eau et des solutés à certains pores en les obstruant ou non. Il a également été observé qu'il est possible de lessiver ces substances humiques par l'application uniforme d'une solution concentrée en chlorure de sodium.

Ces observations, qui bien évidemment se devront d'être confirmées par la poursuite d'expériences supplémentaires, constituent un pas en avant dans la compréhension des processus de transport de solutés dans les milieux artificiels à base de tourbe. La compréhension de ces phénomènes est nécessaire à l'établissement d'une régie d'irrigation optimale favorisant des rendements élevés et des impacts environnementaux moindres avec des substrats plus durables.