

氮磷钾肥不同滴灌撒施组合对富士苹果¹⁵N吸收分配及利用率的影响

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摘要:【目的】探究不同滴灌撒施组合下树体对¹⁵N的吸收分配以及氮肥利用率的影响,旨在获得适宜的肥料滴灌组合。【方法】以2年生烟富3/T337/山丁子为试材,采用盆栽、滴灌袋模拟滴灌施肥方法。设置氮肥(N)、磷钾肥(PK)的滴灌或撒施的5个处理。T1:N撒施,PK滴灌;T2:N撒施,PK撒施(PK为水溶肥);T3:N滴灌,PK滴灌;T4:N滴灌,PK撒施(PK为水溶肥);T5:N滴灌,PK撒施(PK为普通肥料)。【结果】植株各器官的Ndff值均在T3处理下最高,中间砧和毛细根在T3处理与T5处理间有显著差异;主干和主根的¹⁵N吸收量均在T5处理下吸收最高,其他部位的¹⁵N吸收量在T5处理与其他处理间均无显著差异,¹⁵N分配率除主干外其他部位均无显著差异,主干在不同处理间有显著差异,在T5处理下分配率最高(11.24%),T3、T4处理下叶片和枝条的分配率显著高于其他部位;多年生枝的氮肥利用率在T3处理下最高,且与T1处理有显著差异。主干的氮肥利用率在T5处理最高,与其他4个处理均有显著差异。侧根的氮肥利用率在T4处理下最高,与T1、T2处理有显著差异。植株整体的氮肥利用率在T3、T4处理与T1、T2处理间有显著差异,与T5处理无显著差异。【结论】综上所述,实际栽培管理中可以推广氮肥滴灌、磷钾肥撒施普通肥料的施肥方式。

关键词:苹果;滴灌方式;撒施方式;¹⁵N;肥料利用率

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Effect of different combinations of dripping and spreading fertilization of N, P and K fertilizers on uptake, distribution and utilization of ¹⁵N in Fuji apple

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Abstract:【Objective】Fertigation is a new technology for integrated agricultural water and fertilizer management, which can effectively achieve simultaneous supply and efficient use of water and fertilizer. Fertigation technology is widely used in China in the production of maize, tomatoes, bananas and other fruits and vegetables, but the application in apple industry is far behind other countries. We aimed to study the effects of tree uptake, distribution and utilization of ¹⁵N under different combinations of dripping and spreading fertilization of N, P and K fertilizers to obtain the proper way of fertilization.【Methods】The trial was conducted with 2-year-old nursery trees of Yanfu 3/T337/ *Malus baccata* (Linn.) Borkh. as test materials, and the pot test and drip irrigation bags were used to simulate dripping fertilization. Five treatments were set up for dripping and spreading application of nitrogen (N), phosphorus and potassium (PK) fertilizers. T1: N spreading, PK dripping; T2: N spreading, PK spreading (water soluble PK fertilizer); T3: N drip irrigation, PK drip irrigation; T4: N drip irrigation, PK sprinkle (water soluble

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PK fertilizer); T5: N driping, PK spreading (common PK fertilizer). All fertilizers were applied in May, June and July 2019. The amount of fertilizer applied each month was one third of the total fertilizer. The fertilizers used for spreading fertilization in the trial were spread on the pots and then mixed with the soils on the 5th day of each month, 1/3 amount of the fertilizers were used for each month. The fertilizers used for dripping fertilization treatment were used three times for each month at an interval of 7–10 days. All treatments were repeated three times. The total amount of the fertilizers used for each pot (the weight of dry soil in a pot was about 20 kg) was 10 g of N, 5 g of phosphorus pentoxide and 5 g of potassium oxide. The specific fertilizer dosage was calculated based on the actual nutrient content of the fertilizer. The whole plant was covered with a screen net. The leaves were collected in October 2019.

【Results】The total whole plant nitrogen was not significant different among the different treatments, but it was slightly lower under the T1 and T2 treatments (N used by spreading) than those under the T3, T4 and T5 treatment (N used by driping). The nitrogen content of annual branches was highest under the T3 treatment and significantly different from the T5 treatment. The nitrogen content of main roots was highest under the T1 treatment and significantly different from that under the T4 treatment. The total nitrogen of leaves and annual branches was highest under the T3 treatment. The total nitrogen of perennial branches and intermediate rootstock was highest under the T5 treatment. The total nitrogen of the main stems was highest under the T5 treatment and significantly different from those under the other treatments. The total nitrogen of main root was highest under the T1 treatment and lowest under the T3 treatment, and the total nitrogen under the T1 and T5 treatments were significantly higher than that under the T3 treatment. The total N of lateral roots and capillary roots was highest under the T4 treatment. The overall Ndff values of the plants varied with the treatments, and the Ndff values under the N dripping irrigation treatments (T3, T4, T5) were higher than those under N spreading treatments (T1, T2), and were highest under the T3 treatment and significantly different from those under the T1 and T2 treatments. The overall ¹⁵N uptake of the plants varied with the treatments, and the ¹⁵N uptake under N dripping irrigation treatments (T3, T4, T5) were all higher than those under the nitrogen fertilizer spreading treatments (T1, T2), and were highest under the T3 treatment, and was significantly different from those under the T1 and T2 treatments. The Ndff values of the leaves were highest under the T3 treatment and were significantly higher than those under the other treatments. The Ndff values of perennial branches were highest under the T3 treatment which was significantly different from those under the T1 and T2 treatments. The Ndff values of the inter-stock and hair roots were highest under the T3 treatment, and were significantly different from those under the T1, T2 and T5 treatments. Meanwhile, the ¹⁵N uptake of the leaves and annual branches was highest under the T3 treatment. The ¹⁵N uptake of perennial branches was highest under the T3 treatment and was significantly different from that under the T1 treatment. The ¹⁵N uptake of the inter-stock was highest under the T3 treatment. The ¹⁵N uptake of the main stems and main roots was highest under the T5 treatment and was significantly different from those under the other treatments. The ¹⁵N uptake of the lateral roots was highest under the T4 treatment and was significantly different from those under the T1 and T2 treatments. The ¹⁵N uptake of hair roots was highest under the T4 treatment. The overall N fertilizer utilization rate of the plants significantly varied with the treatments, and the highest N fertilizer utilization rate was 28.83% under the T3 treatment, which was 10.13% and 10.56% higher than those under the T1 and T2 treatments, and there was no significant difference between T4 and T5 treatments and T3. The leaf nitrogen fertilizer allocation rate was highest under the T2 treatment and was lowest under the T5 treatment. The N fertilizer distribution rate of the annual branches was highest under the T3 treatment. The N fertilizer distribution rate of the perennial branches was highest under the T2 treatment. The N fertilizer distribution rate of the main stems was highest

under the T5 treatment and was significantly higher than those under the other treatments. The N fertilizer distribution rate of the inter-stock was highest under the T5 treatment. The N fertilizer distribution rate of the main roots was highest under the T1 treatment. The N fertilizer distribution rate of the lateral roots and hair roots was highest under the T4 treatment. The leaf blades and annual branches had the highest N fertilizer utilization rate of 5.80% and 6.72% under the T3 treatment, respectively. The perennial branches had the highest nitrogen fertilizer utilization rate of 5.83% under the T3 treatment, which was significantly different from that under the T1 treatment. The inter-stock had the highest N fertilizer utilization rate of 2.21% under the T3 treatment. The highest N fertilizer utilization rate of the main stems was 2.79% under the T5 treatment, which was significantly different from those under the other treatments. The highest N fertilizer utilization rate of the main roots was 2.84% under the T5 treatment. The lateral roots had the highest N fertilizer utilization rate of 2.92% under the T4 treatment, which was significantly different from those under the T1 and T2 treatments. The hair roots had the highest N fertilizer utilization rate of 4.68% under the T4 treatment. 【Conclusion】 In summary, different combinations of dripping fertilization had different effects on ^{15}N uptake, distribution and utilization in apple trees. The N fertilizer uptake and utilization were highest when all fertilizers were used by dripping. However, the N fertilizer uptake and utilization under N, P, K dripping treatments was not different from that under N dripping fertigation and P, K spreading fertigation treatments. Considering that the costs of the water soluble phosphorus and potassium fertilizers are much higher than those of common phosphorus and potassium fertilizers, it would be recommended that nitrogen fertilizer could be used by dripping and common phosphorus and potassium fertilizers could be used by spreading in practice.

Key words: Apple; Drip irrigation method; Spreading method; ^{15}N ; Fertilizer utilization rate

我国是苹果生产大国,种植面积和总产量均居世界前列。然而,提高果园单产、提升果实品质仍然是我国果业发展亟需解决的问题。施肥是影响果园单产和果实品质的主要措施之一。目前果园的主要施肥方式为沟施和撒施,存在肥效释放慢、肥料利用率低等问题^[1]。滴灌技术起源很早,最初是为了节约用水,水肥一体化技术在此基础上发展而来,水肥一体化又称为滴灌施肥,是一项农业水肥综合管理新技术,能够有效实现水肥同步供应和高效利用。科研人员发现将肥料放于灌溉水中,通过滴灌系统将肥料送到植物根部,植物生长状态更好。目前已广泛用于棉花、玉米、苹果、柑橘等作物和果树的种植^[2]。滴灌施肥可有效调控灌水量和施肥量、确保施肥更加均匀,提高作物的水肥利用效率,使作物的产量和品质都得到可靠保证,具有节水节肥、增产增效的优点。农业发达国家采用滴灌施肥的果园比例为75%~80%^[3-8]。目前,我国水肥一体化技术广泛用于玉米、西红柿、香蕉等瓜果蔬菜的生产,但在苹果产业的应用上还落后于其他国家^[7, 9-12]。

目前果园水肥一体化还存在一系列的问题。如,目前水溶肥市场价格较高,完全实行水肥一体化

普通农户无法承受;氮肥中农用尿素、碳铵、硝铵等肥源水溶性较好,可以直接作为水溶肥,且利用水肥一体化设施进行少量多次施用是提高氮肥利用率的主要途径之一,而常见磷钾肥中农用硫酸钾、磷酸二铵,尤其是常规复合肥水溶性差,不能作为滴灌施肥肥源;完善的水肥一体化设施投资成本高,且需要拥有一定技术的专业人员进行操作和维护,普通果农不具备操作专业水肥一体化设备的能力。

王力等^[7]在西瓜上的研究表明对西瓜进行灌水施肥,达到了节水、节肥、高产和减少化肥对土壤污染的目的。杨凡等^[13]在酿酒葡萄上的研究表明滴灌条件下产量更高。赵佐平等^[14]在苹果上的研究表明水肥施用技术能够显著提高苹果产量和品质。刘星等^[15]在苹果上的研究表明滴灌模式下更利于果树的生长和产量的提高。前人的研究主要集中在相对于传统施肥,滴灌施肥在提高树体生长及果实品质方面的优势,树体在不同肥料滴灌、撒施组合条件下,对肥料吸收利用效率的研究几乎没有。笔者在本研究中以富士苹果为对象,研究不同滴灌组合下树体对 ^{15}N 的吸收分配以及氮肥利用率的影响,旨在获得适宜的肥料滴灌方式,为果树科学的滴灌施肥提供

理论依据。

1 材料和方法

1.1 试验设计与管理

盆栽试验于2019年在辽宁兴城中国农业科学院果树研究所温泉实验基地进行。试材为2年生烟富3/T337/山丁子幼苗,每株3~4个分枝,基部粗度2 cm,所需水肥一体化方式采用滴灌袋模拟。试验共设5个处理,T1:N撒施,PK滴灌;T2:N撒施,PK撒施(PK为水溶肥);T3:N滴灌,PK滴灌;T4:N滴灌,PK撒施(PK为水溶肥);T5:N滴灌,PK撒施(PK为普通肥料)。每个处理3次重复。

所有肥料在2019年5月、6月、7月施入。每月施入肥料的量各占肥料总量的三分之一。试验中用于撒施的肥料分别于月初(每月5日前)一次性撒入盆后与土混匀;用于滴灌处理的肥料,将每月肥料的总量分成等量3次施用,每次间隔7~10 d。所有处理用于撒施的肥料分3次施用完毕,用于滴灌处理的肥料分9次施用完毕。肥料总养分施入量按照每kg土0.5 g氮(N)计算,加仑盆中干土质量约为20 kg,即每盆施入N的总量为10 g。五氧化二磷和氧化钾均按照每盆5 g施用。具体肥料用量根据肥料实际养分含量计算。每月具体施用量见表1(仅列出5月份施用量,6、7月份相同)。2019年10月份

表1 2019年5月份肥料用量

Table 1 Fertilizer dosage for May 2019

处理 Treatment	尿素(农用) Urea (Agricultural)	¹⁵ N尿素 Urea (¹⁵ N)	磷酸二氢钾(试剂) KH ₂ PO ₄ (Reagents)	硫酸钾(试剂) K ₂ SO ₄ (Reagents)	磷酸二铵(农用) (NH ₄) ₂ HPO ₄ (Agricultural)	硫酸钾(农用) K ₂ SO ₄ (Agricultural)	g
T1	5.58	2.00	3.21	1.05			
T2	5.58	2.00	3.21	1.05			
T3	5.58	2.00	3.21	1.05			
T4	5.58	2.00	3.21	1.05			
T5	4.16	2.00			3.62		3.27

用纱网将全株罩住,用于落叶收集。

1.2 测定项目及方法

当年冬季,树体进入休眠期后,将树体解析为叶片、一年生枝、多年生枝、主干、中间砧、主根、侧根、毛细根共8个部位。样品按清水→洗涤剂→清水→1%盐酸→3次去离子水顺序冲洗后,85℃杀青30 min,随后65℃烘干至恒质量,电磨粉碎后混匀装袋备用。

样品消煮全氮用凯氏定氮法测定。¹⁵N丰度用ZHT-03质谱计测定。

各组织氮总量/g=各组织氮含量(%)×各组织干质量(g);

Ndff/%=(植物样品中¹⁵N丰度%−¹⁵N自然丰度%)/(肥料中的¹⁵N丰度%−¹⁵N自然丰度%)×100;

各组织¹⁵N吸收量/mg=各组织全氮含量(mg)×Ndf(%);

氮肥分配率/%=各组织从氮肥中吸收的氮量(mg)/总吸收氮量(mg)×100;

氮肥利用率/%=各组织¹⁵N吸收量(从氮肥中吸收的N)(mg)/同位素N施用量×100。

1.3 数据统计

数据用Excel整理计算后,利用SAS 9.4进行方差分析,利用LSD法进行多重比较。

2 结果与分析

2.1 不同滴灌施肥方式对植株干质量、氮含量及氮总量的影响

由表2可以看出,不同处理间整株干质量、氮总量之间没有表现出显著性差异,但是氮肥撒施的处理(T1、T2)植株氮总量略低于氮肥滴灌的处理(T3、T4),表明氮肥滴灌处理促进了树体对氮的吸收。氮肥滴灌条件下磷钾肥不同施用方式间无显著差异,且当磷钾肥施用普通肥料(T5)与施用水溶性磷钾肥(T3、T4)间也无显著差异。

植株各组织干质量、氮含量和氮总量不同处理间表现出一定的差异性。植株主干的干质量在T3、T4处理高于T1、T2处理,且4个处理间无显著差异,T5处理显著高于其他处理。中间砧的干质量在T4处理最高,与T1处理有显著差异,T5处理与T4处理无显著差异。其余部位的干质量在不同处理下无显著差异。多数部位的干质量在T3、T4处理高于T1、T2处理。一年生枝的氮含量在T3处理最高,与T5处理有显著差异。主根的氮含量在T1处理最高与T4处理有显著差异。其余各部位的氮含量在不同处理下无显著差异。

表2 不同滴灌方式对植株氮含量和氮总量的影响

Table 2 Effect of different drip irrigation methods on nitrogen content and total nitrogen

部位 Plant tissue	处理 Treatment	干质量 Dry weight/g	氮含量 Nitrogen content/%	氮总量 Total nitrogen/g
叶子 Leaf	T1	94.70±4.86 a	1.15±0.29 a	1.09±0.33 a
	T2	99.44±20.45 a	1.33±0.04 a	1.32±0.31 a
	T3	108.61±29.69 a	1.32±0.06 a	1.44±0.46 a
	T4	101.08±0.47 a	1.25±0.31 a	1.26±0.32 a
	T5	91.49±12.72 a	1.07±0.23 a	1.08±0.23 a
一年生枝 Annual branches	T1	73.91±47.40 a	1.29±0.11 ab	0.93±0.53 a
	T2	83.07±16.13 a	1.18±0.09 ab	0.98±0.12 a
	T3	97.92±30.13 a	1.56±0.21 a	1.50±0.27 a
	T4	88.83±22.40 a	1.42±0.24 ab	1.29±0.54 a
	T5	107.63±0.28 a	0.99±0.43 b	1.07±0.47 a
多年生枝 Perennial branches	T1	178.51±5.36 a	0.75±0.11 a	1.34±0.24 a
	T2	202.81±64.85 a	0.76±0.11 a	1.50±0.28 a
	T3	213.79±66.13 a	0.80±0.11 a	1.67±0.29 a
	T4	220.34±6.72 a	0.74±0.09 a	1.64±0.25 a
	T5	173.71±30.64 a	0.89±0.04 a	1.75±0.07 a
主干 Trunk	T1	81.08±6.01 b	0.53±0.04 a	0.43±0.07 b
	T2	73.38±24.71 b	0.44±0.20 a	0.30±0.04 b
	T3	91.09±0.37 b	0.53±0.09 a	0.49±0.08 b
	T4	107.93±1.26 b	0.41±0.06 a	0.44±0.06 b
	T5	149.69±11.18 a	0.62±0.05 a	0.98±0.08 a
中间砧 Intermediate anvil	T1	94.04±7.87 b	0.49±0.07 a	0.46±0.02 a
	T2	123.44±22.86 ab	0.43±0.14 a	0.54±0.27 a
	T3	123.32±33.14 ab	0.52±0.14 a	0.62±0.01 a
	T4	145.31±6.04 a	0.41±0.06 a	0.59±0.06 a
	T5	130.89±27.41 a	0.52±0.13 a	0.78±0.20 a
主根 Main root	T1	112.00±10.38 a	0.88±0.03 a	0.98±0.06 a
	T2	90.87±28.07 a	0.63±0.17 ab	0.55±0.02 ab
	T3	64.87±20.09 a	0.63±0.20 ab	0.43±0.26 b
	T4	82.55±47.98 a	0.62±0.02 b	0.52±0.31 ab
	T5	95.48±41.53 a	0.75±0.01 ab	0.93±0.01 a
侧根 Lateral root	T1	33.13±3.57 a	1.32±0.18 a	0.44±0.11 a
	T2	43.89±22.29 a	1.14±0.32 a	0.47±0.11 a
	T3	40.79±4.38 a	1.36±0.17 a	0.56±0.13 a
	T4	67.86±27.47 a	1.14±0.16 a	0.75±0.21 a
	T5	45.42±13.20 a	1.47±0.17 a	0.53±0.06 a
毛细根 Capillary root	T1	64.03±23.43 a	1.42±0.00 a	0.91±0.33 a
	T2	60.03±16.34 a	1.25±0.13 a	0.74±0.12 a
	T3	38.28±7.57 a	1.61±0.35 a	0.63±0.26 a
	T4	74.55±28.65 a	1.48±0.25 a	1.14±0.61 a
	T5	54.67±10.90 a	1.51±0.08 a	0.71±0.04 a
整株 Whole plant	T1	731.40±70.27 a	—	6.58±0.83 a
	T2	776.91±169.98 a	—	6.40±0.66 a
	T3	778.66±166.86 a	—	7.34±0.81 a
	T4	888.45±38.87 a	—	7.62±0.17 a
	T5	848.98±99.66 a	—	7.82±0.34 a

注:同列不同小写字母表示相同组织不同处理之间有显著性差异($p < 0.05$)。“—”表示此处数据未测定。下同。

Note: Different lowercase letters in the same column indicate significant differences among different treatments of the same tissue ($p < 0.05$). “—” indicates that the data here are not measured. The same below.

叶片的总氮量在T3处理下最高,与其他处理无显著差异。一年生枝的总氮量在T3、T4处理下高于T1、T2处理,各处理间无显著差异。多年生枝的总氮量在T3、T4处理下要高于T1、T2处理,而在T5处理下最高。主干的总氮量在T5处理下最高且与其

他处理有显著差异。中间砧的总氮量在T5处理下最高。主根的总氮量在T1处理最高,T3处理最低,T1、T5处理的总氮量均显著高于T3处理。侧根、毛细根的总氮量在不同处理下无显著差异。植株各组织的总氮含量总体趋势多数为T3、T4、T5处理高于

T1、T2 处理, 即氮肥滴灌处理的干质量、氮含量和总量总体高于氮肥撒施处理, 而磷钾肥不同施用方式影响较小。

2.2 不同滴灌施肥方式对植株 Ndff 值和¹⁵N 吸收量的影响

由表 3 可以看出, 不同处理间植株整体的 Ndff 值和¹⁵N 吸收量有一定差异, 氮肥滴灌处理(T3、T4、T5)的 Ndff 值和¹⁵N 吸收量均高于氮肥撒施处理(T1、T2), 且 T3 处理最高, 与 T1、T2 处理有显著差异。在氮肥滴灌条件下磷钾肥不同施用方式下植株整体的 Ndff 值和¹⁵N 吸收量并无显著差异。

植株各组织 Ndff 值和¹⁵N 吸收量不同处理间表现出一定的差异性。叶片和中间砧的 Ndff 值在 T3、T4 处理下高于 T1、T2 处理, 其中 T3 处理与 T1、T2 处理有显著差异, T5 处理与 T4 处理无显著差异。多年生枝的 Ndff 值在 T3、T4 处理下显著高于 T1、T2 处理, T5 处理与 T3、T4 处理无显著差异。侧根的 Ndff 值在 T3、T4 处理下高于 T1、T2 处理, 其中 T3 处理与 T1 处理有显著差异, T5 处理与 T3、T4 处理无显著差异。毛细根的 Ndff 值在 T3、T4 处理显著高于 T1、T2 处理, T5 处理与 T4 处理无显著差异。其余各组织的 Ndff 值在不同处理下无显著差异, 且 T3、T4 处理高于 T1、T2 处理, T3、T4 处理与 T5 处理差异较小。同时, 一年生枝的¹⁵N 吸收量在 T3、T4 处理高于 T1、T2 处理, T5 处理与 T3、T4 处理无显著差异。多年生枝的¹⁵N 吸收量在 T3、T4 处理高于 T1、T2 处理, 且 T3、T4 处理显著高于 T1 处理, T5 处理低于 T3、T4 处理但无显著差异。主干的¹⁵N 吸收量在 T5 处理最高且显著高于其他处理。中间砧的¹⁵N 吸收量在 T3、T4、T5 处理高于 T1、T2 处理, 且 T3、T4、T5 处理之间差异较小。主根的¹⁵N 吸收量在 T5 处理最高且与其他处理有显著差异。侧根的¹⁵N 吸收量在 T3、T4 处理高与 T1、T2 处理且 T4 处理与 T1、T2 处理有显著差异, T5 处理略低于 T3、T4 处理且无显著差异。植株各组织的 Ndff 值和¹⁵N 吸收量总体趋势多数为 T3、T4、T5 处理高于 T1、T2 处理, 且 T1 与 T2 处理, T3、T4 与 T5 处理间差异较小。即氮肥滴灌处理的 Ndff 值和¹⁵N 吸收量总体高于撒施处理, 在氮肥施用方式不变时, 磷钾肥不同施用方式下 Ndff 值和¹⁵N 吸收量差异较小。表明氮肥滴灌处理促进了树体对氮肥的吸收、征调, 磷钾肥的不同施用方式影响较小。

表 3 不同滴灌方式对植株 Ndff 值和¹⁵N 吸收量的影响

Table 3 Effect of different drip irrigation methods on Ndff values and ¹⁵N uptake

部位 Plant tissue	处理 Treatment	Ndff/%	¹⁵ N 吸收量 ¹⁵ N absorption/mg
叶子 Leaf	T1	6.51±1.05 ABb	72.93±32.81 Aa
	T2	7.11±0.16 ABb	93.69±19.87 Aa
	T3	9.21±0.84 ABCa	134.66±54.36 Aa
	T4	7.70±0.32 BCab	96.51±20.36 AbA
	T5	7.53±0.30 ABb	81.42±20.23 AbA
一年生枝 Annual branches	T1	8.04±0.72 Aa	72.78±36.24 Aa
	T2	7.73±0.84 Aa	75.06±1.10 AbA
	T3	10.47±0.53 Aa	155.93±19.87 Aa
	T4	9.28±1.26 Aa	122.89±65.85 Aa
	T5	7.69±1.97 ABa	86.54±56.94 ABa
多年生枝 Perennial branches	T1	5.98±0.60 Bb	80.67±22.51 Ab
	T2	6.27±0.56 BCb	93.32±8.90 Aab
	T3	8.13±0.61 CDa	135.31±13.29 Aa
	T4	7.67±0.34 BCa	125.48±13.75 Aa
	T5	7.03±0.19 ABab	122.78±1.94 Aab
主干 Trunk	T1	5.63±0.62 Ba	23.95±1.06 Abc
	T2	5.04±1.72 Da	15.37±7.12 Dc
	T3	7.80±0.64 Da	38.11±9.54 Bb
	T4	6.01±1.39 Da	26.72±9.58 Bbc
	T5	6.63±0.19 Ba	64.77±7.13 Ba
中间砧 Intermediate anvil	T1	5.87±0.45 Bb	27.00±3.50 Aa
	T2	5.15±0.65 CDb	28.90±17.59 CDa
	T3	8.25±0.58 CDa	51.23±3.10 Ba
	T4	6.76±1.05 CDab	40.05±10.05 ABa
	T5	6.47±0.41 Bb	51.02±16.19 Ba
主根 Main root	T1	6.32±0.94 ABa	62.39±12.88 Abc
	T2	6.05±1.02 BCda	33.16±4.17 CdC
	T3	8.66±0.27 BCda	36.86±21.15 Bb
	T4	8.33±1.39 ABa	40.75±19.06 ABbc
	T5	7.09±1.49 ABa	65.87±13.28 Ba
侧根 Lateral root	T1	6.63±1.57 ABb	29.98±13.86 Ab
	T2	6.93±0.98 ABab	31.80±3.35 CDb
	T3	9.92±0.29 ABa	55.64±14.55 Bab
	T4	9.27±1.60 Aab	67.83±7.05 AbA
	T5	8.73±0.88 Aab	46.00±0.80 Bab
毛细根 Capillary root	T1	6.98±0.02 ABc	63.66±23.44 Aa
	T2	7.16±0.51 ABc	52.46±5.06 BCa
	T3	9.79±0.39 ABa	61.02±22.66 Ba
	T4	9.36±0.60 Aab	108.49±63.95 ABa
	T5	8.20±0.47 ABbc	58.16±0.26 Ba
整株 Whole plant	T1	51.96±3.83 b	433.35±40.81 b
	T2	51.45±6.45 b	423.76±9.42 b
	T3	72.22±1.68 a	668.77±58.81 a
	T4	64.39±7.94 ab	628.72±89.21 a
	T5	59.36±5.30 ab	576.57±70.82 ab

注: 同列不同小写字母表示相同组织不同处理之间有显著性差异($p < 0.05$); 同列不同大写字母表示相同处理不同组织间有显著性差异($p < 0.05$)。下同。

Note: Different lowercase letters in the same column indicate significant differences among different treatments of the same tissue ($p < 0.05$); Different capital letters in the same column indicate significant differences among different tissues of the same treatment ($p < 0.05$). The same below.

2.3 不同滴灌施肥方式对植株氮肥分配率和氮肥利用率的影响

由表4可以看出,不同处理间植株整体的氮肥利用率有显著差异,T3处理的氮肥利用率最高达到了28.83%,高出T1和T2处理10.13%和10.56%。T3、T4、T5处理间无显著差异。表明氮肥滴灌处理能够提高氮肥利用率,而磷钾肥不同施用方式无显著影响。

植株各组织氮肥分配率和氮肥利用率在不同处理间有一定差异。主干的氮肥分配率在T5处理下最高且显著高于其他处理。其余各组织的氮肥分配率在不同处理下均无显著差异。叶片、一年生枝在T3处理下氮肥利用率最高,分别为5.80%、6.72%。多年生枝在T3、T4处理下氮肥利用率为5.83%、5.41%,与T1处理有显著差异,T5处理的氮肥利用率低于T3、T4处理,但无显著差异。主干在T5处理下氮肥利用率最高为2.79%,与其他处理有显著差异。中间砧在T3、T4、T5处理下氮肥利用率高于T1、T2处理,T5处理与T3、T4处理间无显著差异。主根在T5处理下氮肥利用率最高(2.84%)。侧根在T4处理下氮肥利用率最高(2.92%),与T1、T2处理有显著差异,T5处理与T3、T4处理间无显著差异。其他各组织的氮肥利用率在不同处理间无显著差异。植株各组织的氮肥分配率和氮肥利用率总体趋势多数为T3、T4、T5处理高于T1、T2处理,且T1与T2之间,T3、T4、T5之间无显著差异。表明氮肥滴灌条件有利于氮肥在植株内的分配及提高氮肥利用效率,磷钾肥不同施用方式影响较小。

3 讨 论

植株器官从肥料中吸收分配到的¹⁵N量对该器官全氮量的贡献率(Ndff)反映了植株器官对肥料¹⁵N的吸收征调能力^[16]。在葡萄的研究中表明,在植株体内根部以及叶片对氮肥的竞争能力更强^[17]。前人在苹果中的研究发现,同一器官的Ndff值在滴灌处理条件下要高于撒施处理^[18]。任饴华等^[19]认为水氮耦合使植株各器官对氮的吸收征调能力更强,促进了植株对¹⁵N的吸收。路永莉等^[20]认为水肥耦合在促进植物养分吸收方面效果显著。本试验的结果显示,在N滴灌,PK滴灌水溶肥(化学试剂)、N滴灌,PK撒施水溶肥(化学试剂)、N滴灌PK撒施普

表4 不同滴灌方式对植株氮肥分配率和氮肥利用率的影响

Table 4 Effect of different drip irrigation methods on plant N fertilizer distribution rate and N fertilizer utilization

部位 Plant tissue	处理 Treatment	氮肥分配率 Nitrogen fertilizer distribution rate/%	氮肥利用率 Fertilizer utilization rate/%
叶子 Leaf	T1	16.55±6.01 ABa	3.14±1.41 a
	T2	22.06±4.20 ABa	4.04±0.86 a
	T3	19.86±6.38 Aa	5.80±2.34 a
	T4	15.74±5.47 Aa	4.16±0.88 a
	T5	14.45±5.28 ABCa	3.51±0.87 a
1年生枝 Annual branches	T1	16.47±6.81 ABa	3.14±1.56 a
	T2	17.72±0.13 ABa	3.24±0.05 a
	T3	23.28±0.92 ABa	6.72±0.86 a
	T4	18.99±7.78 Aa	5.30±2.84 a
	T5	14.51±8.09 ABa	3.73±2.45 a
多年生枝 Perennial branches	T1	18.94±6.98 Aa	3.48±0.97 b
	T2	22.00±1.61 Aa	4.02±0.38 ab
	T3	20.22±0.21 Aa	5.83±0.57 a
	T4	20.32±5.07 Aa	5.41±0.59 a
	T5	21.48±2.97 Aa	5.29±0.08 ab
主干 Trunk	T1	5.54±0.28 Bb	1.03±0.05 bc
	T2	3.65±1.76 Bb	0.66±0.31 c
	T3	5.78±1.94 Db	1.64±0.41 b
	T4	4.18±0.93 Bb	1.15±0.41 bc
	T5	11.24±0.14 Ca	2.79±0.31 a
中间砧 Intermediate anvil	T1	6.30±1.40 ABa	1.16±0.15 a
	T2	6.87±4.30 ABa	1.25±0.76 a
	T3	7.71±1.14 CDa	2.21±0.13 a
	T4	6.32±0.70 Ba	1.73±0.43 a
	T5	8.74±1.73 BCa	2.20±0.70 a
主根 Main root	T1	14.60±4.35 ABa	2.69±0.56 a
	T2	7.84±1.16 ABa	1.43±0.18 a
	T3	5.39±2.69 CDa	1.59±0.91 a
	T4	6.76±3.99 Ba	1.76±0.82 a
	T5	11.37±0.91 ABCa	2.84±0.57 a
侧根 Lateral root	T1	7.10±3.87 ABa	1.29±0.60 b
	T2	7.50±0.62 ABa	1.37±0.14 b
	T3	8.45±2.92 CDa	2.40±0.63 ab
	T4	10.98±2.68 Ba	2.92±0.30 a
	T5	8.05±1.13 ABCa	1.98±0.03 ab
毛细根 Capillary root	T1	14.50±4.04 ABa	2.74±1.01 a
	T2	12.37±0.92 ABa	2.26±0.22 a
	T3	9.31±4.21 BCa	2.63±0.98 a
	T4	16.70±7.80 Ba	4.68±2.76 a
	T5	10.16±1.20 ABCa	2.51±0.01 a
整株 Whole plant	T1	—	18.68±1.76 b
	T2	—	18.27±0.41 b
	T3	—	28.83±2.54 a
	T4	—	27.10±3.85 a
	T5	—	24.85±3.05 ab

通肥料时,叶片、多年生枝、中间砧、侧根、毛细根的Ndff值要高于N撒施,PK滴灌水溶肥(化学试剂)、N撒施,PK撒施水溶肥(化学试剂)处理。由此说明,水溶性氮肥更利于树体对于氮素的吸收征调。氮肥保持施用方式不变时,磷钾肥滴灌或撒施对植株的Ndff值并无显著影响。

不同滴灌方式不仅影响植株器官的Ndff值,还影响了各器官的氮素的分配。各器官中¹⁵N占全株¹⁵N总量的百分比反映了肥料¹⁵N在树体内的分布及其在各器官间迁移的规律^[17]。本试验中叶片在N撒施,PK撒施水溶肥(化学试剂)处理是氮肥分配率最高,说明撒施处理利于营养器官的生长。这与赵林等^[21]的研究结论一致。田歌等^[18]的研究也认为撒施处理有利于营养器官的生长。滴灌施氮处理下一年生枝、主干、中间砧、侧根、毛细根的氮肥分配率更高,说明氮肥滴灌处理有利于提高树体贮藏器官的营养水平以及第2年新生器官的建造^[18]。本试验不同施肥处理下,叶片和枝条的分配率均高于其他部位。与前人研究中植株体内氮素更易向生命活动更活跃的区域移动^[17, 22]的结论相一致。T3、T4处理下叶片和枝条的分配率显著高于其他部位。说明滴灌更利于氮素向生长活跃区域移动。

苹果的养分吸收主要依靠根系对土壤中养分的吸收能力,土壤中养分的移动性决定了根系养分的吸收效率,因此水肥一体化更有利根系吸收养分^[23]。前人研究表明,如果施氮过浅,暴露在地表的氮肥容易挥发,从而难以被根系吸收^[18, 24]。并且,如果撒施氮肥,肥料更加难以进入果树的根层,雨水和灌溉会造成一定的损失,导致氮肥利用率低。任饴华等^[19]认为水量是限制苹果氮素利用的重要因素,水氮耦合能够提高氮肥利用率。滴灌施肥弥补了传统灌溉与施肥分离的不足,使水肥均匀地作用到作物的根区,滴灌处理的苹果根系主要活动层较常规条件深,根系分布广、活力增强,吸收根多,能够增加作物对肥料的吸收^[25]。路永莉等^[26]认为水肥一体化技术在同等施肥量下能够明显提高养分和水分的利用效率,同时也有助于降低果园的养分流失量。本试验中氮肥滴灌条件下植株各器官的氮肥利用率更高,与前人的研究相似。在氮肥滴灌的条件下,磷钾肥滴灌会比撒施氮肥利用率更高,周兴本等^[27]在葡萄中的研究发现提高磷钾肥比例可以提高葡萄植株的氮肥利用率,说明磷钾肥能够促进氮肥的吸收。

目前水肥一体化技术还存在着一定的限制因素。比如,设备建设资金投入大,技术人员匮乏,农民缺乏认识,生产技术落后,国内规模化生产水溶性肥料的企业较少,生产工艺缺乏创新性,生产技术方面仍然比不上发达国家,农民对国内产品信任度不高等^[28-29]。近年来,国内水溶性肥料的需求量和市场规模不断扩大,然而,由于国内水溶性肥料生产技术存在缺陷,进口水溶性肥料仍占较高的市场份额。市面上水溶性肥料的种类繁多,产品质量参差不齐,时常出现假冒伪劣产品^[30]。在果农施肥过程中,氮肥中尿素、碳铵、硝铵等水溶性很好的氮肥便可作为水溶肥进行滴灌使用,而农用磷酸二铵、过磷酸钙、农用硫酸钾、常规复合肥等水溶性差,不能应用于滴灌系统。市场常见大量元素水溶肥价格是普通复合肥的4倍左右。

肥料中氮、磷、钾施入土壤后,除了被植物所吸收利用的部分外,一部分以各种途径损失(离开土壤),一部分留存在土壤中进入无效化过程。其中,氮肥在土壤中的转化以气态损失和淋溶损失为主,而施入到土壤中的磷钾肥则大部分进入到无效过程,积累于土壤中。生产中氮肥采用滴灌方式,可以实现少量多次施用以达到减少损失的目的。相对于滴灌方式,磷钾肥撒施必然也会造成磷钾肥当季利用率的降低。然而,磷钾肥残效长,相对损失少,在保证植株当季可利用养分足够的前提下,可以采用撒施普通肥料的方式。因此,生产中可以推广氮肥滴灌普通尿素,磷钾肥撒施常规肥料以实现节约生产成本的目的。

4 结 论

综上所述,不同的滴灌组合对树体¹⁵N吸收和分配利用的效果不同。当全部肥料滴灌的时候氮肥吸收量及利用率最高,但与氮肥滴灌、磷钾肥撒施无显著性差异。考虑到磷钾水溶肥料的使用成本远远高于普通磷钾肥料,因此,在生产中可以考虑采用氮肥滴灌、磷钾肥撒施普通肥料的施肥方式,在保证满足果树树体养分需求、提高肥料利用率的情况下最大限度地降低果园管理的生产投入成本。

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