Plant Soil (2024) 495:699–722
https://doi.org/10.1007/s11104-023-06361-4

RESEARCH ARTICLE

In a nutshell: almond hull and shell organic matter amendments increase soil and tree potassium status

Ellie M. Andrews · Daniel J. Rivers · Amélie C. M. Gaudin · Daniel Geisseler · Patrick H. Brown · Sat Darshan S. Khalsa

Received: 8 August 2023 / Accepted: 16 October 2023 / Published online: 7 November 2023

Abstract
Background Crop residues used as organic matter amendments have been shown to release potassium (K) into the soil, promoting K cycling in agronomic systems. Orchard field trials are needed to evaluate K dynamics under almond hull and shell amendments, which contain high K concentrations.
Methods Three field trials in commercial almond orchards were conducted to assess the effects of surface-applied almond hull and shell amendments on K cycling within plant and soil systems. Amendment K concentrations over time, soil exchangeable K, and tree K status were measured as well as decomposition rate and crop yield.
Results Hulls and shells released K rapidly under irrigation and rainfall, significantly increasing soil exchangeable K in the upper 0–10 cm soil within 2–7 weeks. Amendments increased tree leaf K status within the first 1–3 years to varying degrees depending on site. Initial amendment K concentrations decreased by at least half by dry weight within the first 25.4 cm (10 inches) of water (irrigation and precipitation) within the irrigated zone.
Conclusions Almond hulls and shells can increase soil and plant K status when used as amendments on the soil surface. This practice can address byproduct utilization issues, recycle potassium (K), and reduce orchard K fertilizer demand by replacing the majority of tree K demand. Growers can tailor application rates to meet orchard-specific K management goals. Off-ground harvest preserved the hull/shell organic layer over time and maximized K cycling. Hull/shell amendments applied on the soil surface cover more soil area within the irrigated wetted zone compared to banded K fertilizer. This practice can reduce reliance on K fertilizers and reduce associated costs while providing a convenient outlet for hulls and shells.

Keywords Potassium · Organic matter amendments · Recycling · Soil · Orchard

Responsible Editor: Peter Christie.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11104-023-06361-4.

E. M. Andrews (✉)
University of California Agriculture and Natural Resources Cooperative Extension, Santa Rosa, CA 95403, USA
e-mail: eandrews@ucanr.edu

D. J. Rivers
University of California Agriculture and Natural Resources Cooperative Extension, Stockton, CA 95206, USA

A. C. M. Gaudin · P. H. Brown · S. D. S. Khalsa
Department of Plant Sciences, College of Agriculture and Environmental Sciences, University of California Davis, Davis, CA 95616, USA

D. Geisseler
Department of Land, Air and Water Resources, College of Agriculture and Environmental Sciences, University of California Davis, Davis, CA 95616, USA

Abbreviations

K Potassium

XK Exchangeable potassium

Introduction

Applying nutrient-rich crop residues as soil organic matter amendments can be an efficient strategy for recycling crop byproducts (Andrews et al. 2021). Potassium is highly mobile in plant cells and releases rapidly from crop residues into soil solution under water application (Brito et al. 2014; Dong et al. 2019; Hougni et al. 2021; Rodríguez-Lizana et al. 2010). The K stored in crop residues can be reused within crop systems to increase soil exchangeable potassium (XK) and plant K status over time. Soil XK has been shown to increase under tree crop byproducts such as cacao husk amendments (Doungous et al. 2018; Agele and Agbona 2008), coffee husks (Carmo et al. 2016), pecan husks (Idowu et al. 2017), and macadamia nutshells (Bittenbender et al. 1998; Lobel et al. 1994). Foliar K status has been shown to increase under amendments of macadamia husks (Lobel et al. 1994; Nagao et al. 1992) and cacao pod husks (Agele and Agbona 2008). While increased soil XK levels under K-rich crop residues are common, fewer studies report significant increases in leaf K status. This may be partially attributed to a dilution effect where increased growth and leaf biomass can lead to minimal relative increases in leaf K concentration (Zeng et al. 2001). Given the lack of field trials evaluating hull/shell amendments in mature commercial orchards and potential dilution effects, multi-year field trials are needed to evaluate potential improvements in K cycling and tree K status over time.

Annual almond tree K demand commences in early spring, peaks during summer fruit enlargement and kernel fill, and diminishes following hull split (Muhammad et al. 2020). Productive almond trees have high potassium (K) demand. In typical mature almond orchards with high yields, annual K allocation can range from approximately 20–50 kg K ha^{-1} in perennial organs, 20–45 kg K ha^{-1} in annual leaf biomass, and 265–390 kg K ha^{-1} in fruits (Muhammad et al. 2015, 2018, 2020). Almond fruit tissues are the main sink for nutrients in almond trees. They consist of a kernel surrounded by a shell and an outer hull. Prior research indicates that as much as 91% of whole tree annual K demand can accumulate in almond fruit which was exported from the orchard at harvest at approximately 75 kg K per metric ton of kernel yield (Muhammad et al. 2015, 2018). At processing facilities, kernels are separated from hulls and shells which comprise approximately 70% of crop fresh weight leaving the orchard at harvest (Almond Board of California 2020). Applying hulls and shells as amendments in orchards could provide a cost-effective source of recycled K and other nutrients, with potential soil health and soil carbon benefits. Within a nutrient budget framework, this practice offers an efficient strategy to resupply crop system K by using crop byproducts.

Prior research indicates that K-rich mulches can be used to address K deficiencies in orchards in semi-arid regions and increase tree leaf K concentrations and yields (Neilsen et al. 2002, 2003). In apple orchards, researchers noted the tradition of using mulches to address K deficiency (Neilsen et al. 2014). Tree crop pericarp materials (e.g., pecan, cacao, coffee, etc.) can be used to supplement or substitute fertilizer K, which is beneficial when K fertilizer is financially or logistically difficult to access (Andrews et al. 2021). Crop byproducts have been shown to be a cost-effective alternative to expensive fertilizers in cocoa crop systems (Kone et al. 2020; Oyewole et al. 2012). Increased use of organic residues can help address yield limitations in K-deficient soils and replenish intensively managed soils that have become depleted of K over time. While most almond orchards in California are harvested using on-ground equipment that sweeps the soil surface bare, off-ground harvest equipment that minimizes soil disturbance could be used to preserve the hull/shell amendment organic layer over time. Maintaining the amendment layer on the soil surface during and after harvest could increase total K release potential and associated tree K status.

Recycling K-rich crop residues as organic matter amendments can enhance crop system K reservoirs and reduce dependence on K fertilizers (Drinkwater and Snapp 2007; Jiang et al. 2019; Kasongo et al. 2011; Sui et al. 2015). The high K concentrations of almond hulls and shells indicate these materials could provide significant K for plant uptake. However, field trials are needed to assess how much K can be provided by hull and shell amendments, when it becomes available, and to what degree this practice increases soil XK and plant K uptake. While prior research has consistently demonstrated that K releases rapidly from crop residues under water application, few field trials have specifically evaluated tree crop residue K cycling in the orchard setting.

The objective of this project was to evaluate the effects of almond hull and shell amendments on K cycling in three different orchard field trials to contribute to an integrated framework for K management in tree crop systems. While some California almond growers had already begun adopting this practice, no prior research had been conducted evaluating almond hull/shell materials as K-rich amendments in orchards, thus field trials were needed. Each field trial was approached as a unique case study to assess K cycling dynamics (e.g., hull/shell K concentrations over time, soil XK levels, and plant K status). Our research question asked whether almond hulls and shells can be effectively used as a soil amendment to supply K to meet almond crop demand. We hypothesized that surface-applied hull/shell amendments would solubilize K under water application and increase soil XK within the first several months after amendment application. Hull/shell amendment K at appropriate rates would provide sufficient K to almond trees to maintain optimum leaf K status. Since all sites were commercial orchards with historically sufficient K fertilizer inputs, and no alterations to existing K fertilizer practices were made, no effect on yield was expected. Similarities and differences between sites are highlighted regarding K release, soil XK, and tree K status over time. While the composted hulls/shells utilized in this study at Site 2 contained higher initial K concentration than fresh hulls/shells at the same site, release rates were hypothesized to be similar due the soluble nature of K in plant tissues. Maintaining the hull/shell layer over time with off-ground harvest equipment was hypothesized to maximize K release and K cycling benefits. Findings can be used to inform sustainable nutrient management practices and tailor amendment application strategies to meet the needs of different crop systems.

Materials and methods

Site descriptions

Almond hulls and shells were stockpiled at a processing facility located 1.6 km from the orchard that hosted Trial 1 in the Northern San Joaquin Valley, California (37°39' N 121°25' W, Fig. 1). 'Independence' variety almond trees on 'Viking' rootstock were planted in 2010 at this site. Tree spacing was

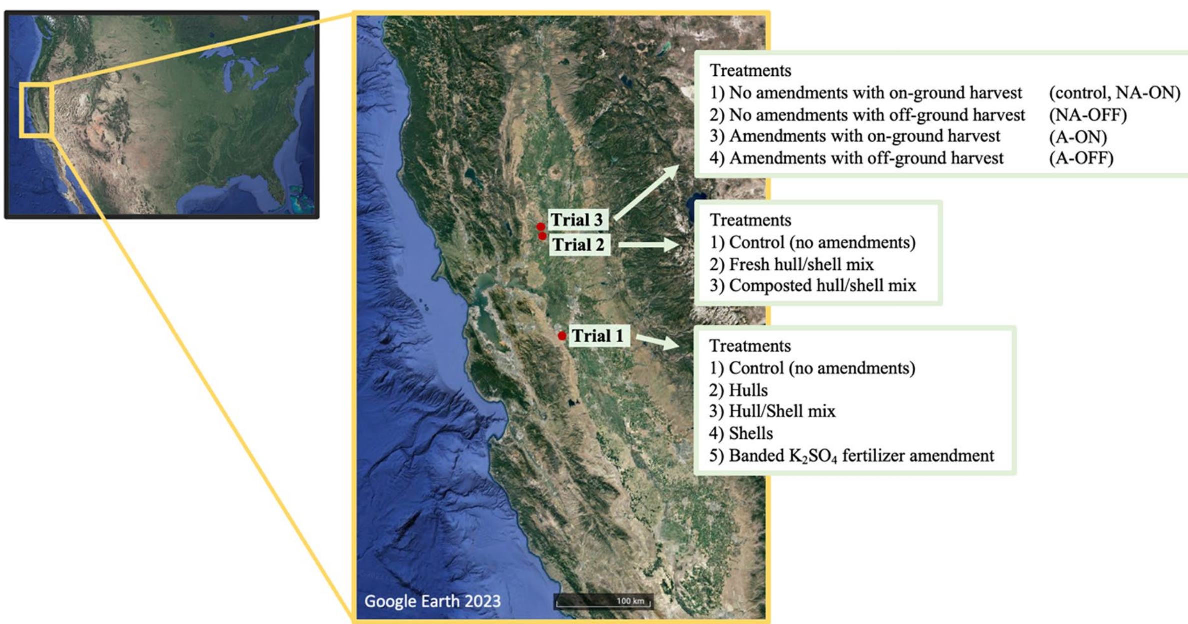

Fig. 1 Aerial image of approximate locations of each field trial and treatments at each site

4.6×5.8 m (15×19 ft) and trees were drip irrigated. The soil type was Capay clay (NRCS, Supplementary Table 1). Typical fertilizer management practices included the application of 13–46 kg ha^{-1} (12–41 lb ac^{-1}) K annually applied as potassium thiosulfate fertilizer through the drip irrigation system during the spring.

The second and third trials were located near Woodland in the Sacramento Valley, California, and sourced almond nutshell materials from a processor located approximately 24 km from the orchards. Treatments were applied to 'Nonpareil' variety only at Trials 2 and 3. Growers at Trial 2 (38°38' N 121°50' W, Fig. 1) produced compost using a mixture of approximately 70% almond hulls/shells and 30% dairy manure. 'Nonpareil' variety almond trees on 'Titan' rootstock were planted in 2015 with alternating pollinizer varieties. Tree spacing was 5.5×7.3 m (18×24 ft) and trees were drip irrigated. The soil type was Sycamore silty clay loam soil (NRCS, Supplementary Table 1). At this site, growers reported approximately 224 kg ha^{-1} (200 lb ac^{-1}) K fertilizer was uniformly applied across the entire orchard in 2021 through the drip irrigation system across sixteen irrigation events from March-June.

To evaluate whether reduced soil disturbance could increase amendment K cycling, Trial 3 (38°40' N 121°53' W, Fig. 1) was designed to evaluate a hull/shell mix amendment paired with off ground harvest equipment to minimize soil disturbance in the tree row and maintain the amendment layer. 'Nonpareil' variety on 'Bright Hybrid 5' rootstock were planted in 2014 with alternating pollinizer row varieties. Trees were spaced at 4.6×6.7 m (15×22 ft) and were micro-sprinkler irrigated. The soil type was San Ysidro loam (NRCS, Supplementary Table 1). In 2020, approximately 202 kg ha^{-1} (180 lb ac^{-1}) K was applied uniformly across the entire orchard as potassium nitrate fertilizer through the irrigation system split over 15 fertigation events.

No alterations were made to existing fertilizer management practices at all trials; hull/shell amendments were applied in addition to established fertilizer applications. This ensured that the trials would not lead to potentially detrimental K deficiencies in the event that K did not readily solubilize. The critical value ranges for California almond July leaf K concentrations are well-established. Increases in soil XK can lead to increases in leaf K status within the leaf K sufficiency range, which allowed the assessment of treatment effects at these sites where leaf K was already adequate. Maintaining the established K fertilizer best management practices at each trial was a conservative approach to assessing K dynamics that minimized the risk of severe K deficiencies at the cooperating commercial orchards.

Experimental design

Each field trial was approached as a case study to assess K cycling dynamics at three unique commercial orchards with different management practices, thus each site had a different set of hull/shell treatments. No statistical comparisons were made across sites—only within sites. All trials were randomized complete block designs with each treatment applied to an entire tree row. One buffer tree row was located between each tree row receiving a treatment. Each experimental unit consisted of at least 40 trees within an individual treatment tree row, hereafter referred to as a plot. Each plot was replicated in four blocks and assigned to a random row within each block. At each orchard, trial location was informed by NRCS soil web database maps to identify an area of a consistent soil type. Hull/shell amendments were applied with a compost spreader that placed materials only in the tree row area and not in the alley, except for the fall 2020 application at Trial 3 which was broadcasted.

Precipitation data was sourced from the California Irrigation Management Information System (CIMIS) databases, Station 249 (Ripon) for Trial 1, and Station 226 (Woodland) for Trials 2 and 3. Irrigation data was provided from water meter readings at the pump station at Trial 1 and grower records at Trials 2 and 3. Irrigation was applied through drip lines at Trials 1 and 2 and micro sprinklers at Trial 3. Precipitation and irrigation data was collected beginning at amendment applications in the fall of 2020 at all trials. Since the wetted soil surface area ranged from approximately 20–58% of total soil surface area depending on irrigation system, applied irrigation was converted to a centimeter (cm) in the wetted area basis utilizing the approximate wetted area for each orchard and integrated with rainfall data. An example is shown in Eq. 1 below. Wetted soil area was estimated to be 58% of total soil area at Trial 1, 45% at Trial 2, and 20% at Trial 3. At all trials, all amendment and soil samples were collected from within the irrigated wetted zone. Therefore, the data, model, and results presented in this paper only represent K cycling that occurred within the irrigated wetted zone and not the entire orchard soil surface area.

$$\frac{8.8\,cm\,irrigation}{0.58\,ha\,wetted\,area\,ha^{-1}\,total\,area}\text{thus, }\frac{(8.8)}{0.58} = 15.2\,\text{cm within the wetted soil area} \quad (1)$$

At Trial 1, five treatments consisted of a control (no amendments), hulls, shells, a mix of hulls and shells, and a banded potassium sulfate fertilizer amendment. By dry weight, the hull/shell mix treatment consisted of 82% hulls and 18% shells in February 2020 and 91% hulls and 9% shells in November 2020. The hulls, shells, and mix treatments were applied to both sides of trees in designated plots as close as possible to 140 kg ha^{-1} (125 lb ac^{-1}) K during the first application on 2/10/2020 and 185 kg ha^{-1} (165 lb ac^{-1}) K during the second application on 11/12/2020. The goal was to apply the three hull/shell amendments at rates that would provide similar K inputs per acre. The fifth treatment at this site consisted of banded potassium sulfate fertilizer that was applied in fall 2019 and fall 2020 at 230 kg ha^{-1} (205 lb ac^{-1}) (approximately 103 kg K ha^{-1} or 92 lb K ac^{-1}). A minimal baseline K fertilizer application of 34 kg ha^{-1} (30 lb ac^{-1}) K was applied in 2020 across the entire orchard uniformly, within all treatments (including the control) as a precautionary measure to prevent K deficiencies.

Treatments at Trial 2 consisted of a control (no amendments), a mix of fresh hulls/shells, and mature compost comprised of manure and hulls/shells. The fresh hull/shell amendment applied on 10/14/2020 consisted of 20% hulls and 80% shells. This treatment was applied at approximately 12.3 fresh metric tonnes (Megagrams) per hectare (5.5 US tons ac^{-1}) at 18% moisture containing approximately 155 kg ha^{-1} (138 lb ac^{-1}) K. On the same day, the compost was applied at approximately 21 fresh metric tonnes ha^{-1} (9.4 US tons ac^{-1}) at 32% moisture containing approximately 256 kg ha^{-1} (228 lb ac^{-1}) K. The following autumn on 11/29/2021, the fresh hull/shell mix consisted of 40% hulls and 60% shells, and was applied at approximately 18 fresh metric tonnes ha^{-1} (8 US tons ac^{-1}) at 31.8% moisture containing approximately 315 kg ha^{-1} (281 lb ac^{-1}) K. The compost was applied the same day at 29 fresh metric tonnes ha^{-1} (13 US tons ac^{-1}) at 57.6% moisture containing 128 kg ha^{-1} (114 lb ac^{-1}) K. Moisture content of both amendments was higher in 2021 likely due to heavy October rains prior to application.

At Trial 3, two harvest types, on vs. off ground harvest, were included to evaluate whether maintaining the hull/shell amendments over time as an undisturbed organic layer on the soil surface via off ground harvest might influence soil and plant K status differently than the current standard practice of on ground harvest. Four treatments consisted of (1) a control, no amendments and on ground harvest (NA-ON), representative of current almond management practices in California, (2) no amendments and off ground harvest (NA-OFF) to reduce soil disturbance, (3) a hull/shell amendment disturbed by on ground harvest each August (A-ON), and (4) the same hull/shell amendment maintained over time with off ground harvest (A-OFF). On 10/7/2020, 18 metric tonnes ha^{-1} (8 US tons ac^{-1}) of fresh hull/shell mix (32% hulls and 68% shells) with 6.6% moisture were broadcasted across the soil surface including the alley, containing approximately 310 kg ha^{-1} (277 lb ac^{-1}) K. A year later on 10/4/2021, 18 metric tonnes ha^{-1} (8 US tons ac^{-1}) of fresh hull/shell mix (53% hulls and 47% shells) with 2.1% moisture containing 269 kg ha^{-1} (329 lb ac^{-1}) K were applied in the tree row only, concentrating the amendment over tree roots.

Amendment nutrients and decomposition

Amendment samples were collected at application and over time from decomposition litter bags. Net dry mass remaining was used to assess decomposition trends over time for each amendment type. This litter bag protocol was developed in forest ecosystem litter layer research and has been adapted in many agricultural systems to study plant residue decomposition (Kaushal et al. 2012; Krishna and Mohan 2017; Dong et al. 2019; Yang et al. 2020; Prescott and Vesterdal 2021). Prescott and Vesterdal 2021, recommend describing the remaining biomass in litter bags as “net mass remaining” because some fraction of the measured biomass within the bags likely consists of microbial biomass and byproducts, in addition to lingering plant residue. Square litter bags made of 0.08 cm nylon mesh (Memphis Net and Twine Company) 20 cm × 20 cm in size were filled with the appropriate dry mass of each amendment on based on application rates (dry mass per area) and percent moisture. Litter bags were installed immediately after amendment application at all sites in the fall of 2020 and collected at multiple time points during the following year. Three litter bags were collected within each plot at each sampling time. At all sites, three amendment samples per plot were collected, oven-dried at 60 °C, and weighed for net dry mass remaining. Then, samples were pulverized and the three subsamples were aggregated by plot prior to nutrient analysis for nitrogen, phosphorus, potassium, sulfur, boron, calcium, magnesium, zinc, manganese, iron, copper, sodium, and carbon. Carbon and nitrogen were analyzed via flash combustion, while all other elements were analyzed via digestion and inductively coupled atomic emission spectrometry (ICP-AES).

Soil nutrients

Prior to amendment application, soil samples were collected from each plot to assess soil XK. Initial soil samples were taken at 0–10 cm, 10–20 cm, and 20–30 cm depths within the irrigated wetted zone at each site. Additional soil samples were taken and analyzed for XK at later time intervals following each amendment application at all sites. In each plot, three subsamples were collected, air dried, and ground separately with a soil grinder (Test Mark Industries, Soil Grinder SA-1800). Subsamples were aggregated within each plot prior to analysis to provide more representative samples per plot. Soil XK was determined via ammonium acetate extraction (Thomas 1982) and quantification via ICP-AES.

Tree nutrient status and yield

Three healthy, representative sample trees were selected in each plot for annual leaf samples. To assess mid-July leaf nutrient status, 100 leaves were collected per tree, washed twice with DI water, oven-dried, pulverized, and analyzed for K via extraction with a solution of 2% acetic acid and quantification via ICP-AES (Jones 2001; U.S. EPA method 200.7 2021). Yield data for each plot was collected by mechanically sweeping and weighing total fruit fresh weight. One subsample of at least 2.7 kg almond fruit per plot was collected, weighed fresh, oven-dried, weighed dry, and used to calculate percent moisture. Then, dry almond fruits were separated from debris (e.g., sticks, dirt, amendments, etc.) and the fruits and debris fractions were weighed separately. Hull/shell debris was separated from all other debris and weighed. For each sample, one hundred dry whole fruits were separated into kernels, shells, and hulls and weighed. Crack out percentage was calculated as the kernel dry mass as a percentage of whole fruit dry mass. Kernel yield per plot was estimated using dry kernel weight divided by the plot area covered.

Data analysis and statistics

Data was analyzed in R (R Core Team 2022). Most data visualization was performed using the package ggplot2 (Wickham et al. 2016). Response variables were modeled using linear mixed effects models using the lmerTest package (Kuznetsova et al. 2017) as a function of treatment (a fixed effect) and block (a random effect). For July leaf K, subsamples were not aggregated prior to analysis therefore plot was included as a random effect nested within block. Model assumptions of normality and homogeneity of variances were assessed with diagnostic plots, Normal Quantile–Quantile and Scale-Location plots. After diagnostics, analysis of variance (ANOVA) was performed, and Compact Letter Display (CLD) groupings were generated using the estimated marginal means using the multcomp package (Hothorn et al. 2008) for multiple pair-wise comparisons (Tukey method). Alpha values were consistently set to 0.05. When considering data that was successively sampled, treatment, time, and the interaction of treatment and time were included in a linear mixed model to account for repeated measures over time within the same experimental unit. Linear regressions were performed using packages ggpubr (Kassambara 2023) and ggpubmisc (Aphalo 2016) to assess decomposition over time with net mass remaining data.

The R packages lme4 (Bates et al. 2015), mgcv (Wood 2011), nlme (Pinheiro et al. 2023), and performance (Ludecke et al. 2021) were used to develop and evaluate K release models. Trial 1 amendment K concentration data from February until late July 2020 was modeled as a function of corresponding cumulative water applied (rainfall and irrigation within the irrigated wetted zone) to develop a model that provides a framework for predicting changes hull/shell K concentrations over time. Several nonlinear and generalized additive models (GAMs) were evaluated and compared using normality of residuals assessment and ANOVA. GAMs were created and compared by generating Aikake Information Criterions (AICs) and assessing posterior predictive checks, linearity, homogeneity of variances, and normality of residuals (mgcv and performance packages). However, AICs of all GAMs were higher than the AIC of the best nonlinear mixed effects model.

The most parsimonious K release model was a nonlinear mixed-effects model (lme4 package) that allowed treatment effects in all parameters including Y0 (the y-intercept) and had the lowest p-value and AIC. As described in the results section, this model used symbols as in R, e.g., "~" indicates "is modeled as" in Eq. 2. The first part of the model was a typical exponential formula, while C0 was the height at which amendment K concentration (a percentage) ends, which added model flexibility. Y0 was equal to the y-intercept, the original K concentration in the material. B0 was a parameter that regulated the change in steepness of the curve with units that were the reciprocal of cumulative water.

Results

Initial nutrients prior to application

Initial average amendment nutrient concentrations are provided in Table 1, and by trial and year in Supplementary Tables 2–4. The K concentration of the hull/shell mix amendments ranged from approximately 1.5–2.9% K. Hulls generally contained higher K concentrations than shells. Composted hull/shell materials had initial concentrations of approximately 1.0–1.8% K. Factors that may influence hull/shell K concentration include almond variety type, fertilization and irrigation practices, and soil type at the source location (Andrews et al. 2021). At the given rates, hull/shell amendment applications provided small quantities of micronutrients and very low levels of potentially toxic elements, such as boron and sodium.

Decreases in amendment K concentrations over time

At Trial 1, nutrient analyses of amendment samples indicated that K release from hull/shell amendments increased rapidly in the second month with the majority released by early April (Fig. 2). All three amendment materials significantly decreased in K concentration within the first six and a half weeks. After two months, amendment K concentrations remained relatively stable and significantly lower than respective initial K concentrations for all three materials. Most of the K release occurred within the first 6.4 cm (2.5 in) of water, which included both rainfall and irrigation in the wetted zone, before reaching a plateau. By late July 2020, all hull/shell amendments had declined by at least half of their initial K concentrations under approximately 142 cm (56 in) of cumulative water within the wetted zone (Fig. 2, Table 5). The second application of amendments at Trial 1 occurred on 11/12/2020. Between November 2020 and late July 2021, amendment K concentrations significantly decreased by approximately two-thirds of total initial K concentrations under approximately 224 cm of cumulative water (88 in) in the wetted zone.

At Trial 2, K concentration significantly decreased over time in both amendments (Fig. 3a). Two months after application with approximately 3.3 cm (1.3 in) of cumulative water, K concentration was significantly lower in both treatments than respective initial concentrations. This period of rapid K release was followed by a plateau for both fresh hull/shell and composted hull/shell/manure amendments. From October 2020 until August 2021, amendments declined by approximately two thirds of initial K concentrations under approximately 178 cm (70 in) of water in the irrigated wetted zone (Fig. 3b). On average, fresh

Table 1 Average nutrient concentrations in hull ($n=11$), hull/shell mix ($n=26$), shell ($n=23$), and mix-based compost ($n=8$) materials applied at all field trials across all years

Material	C:N	(%)						(ppm)						
		C	N	P	K	Ca	Mg	S	B	Zn	Mn	Fe	Cu	Na
Hulls	63:1	39.8	0.63	0.09	2.4	0.2	0.11	286	121	5	12	204	3	153
Mix	55:1	41.8	0.79	0.08	2.4	0.2	0.10	314	100	8	15	350	3	155
Shells	76:1	41.3	0.57	0.05	1.5	0.2	0.08	248	58	6	18	477	3	122
Compost	29:1	27.2	0.96	0.18	1.4	0.8	0.92	1476	87	88	385	19,357	31	1628

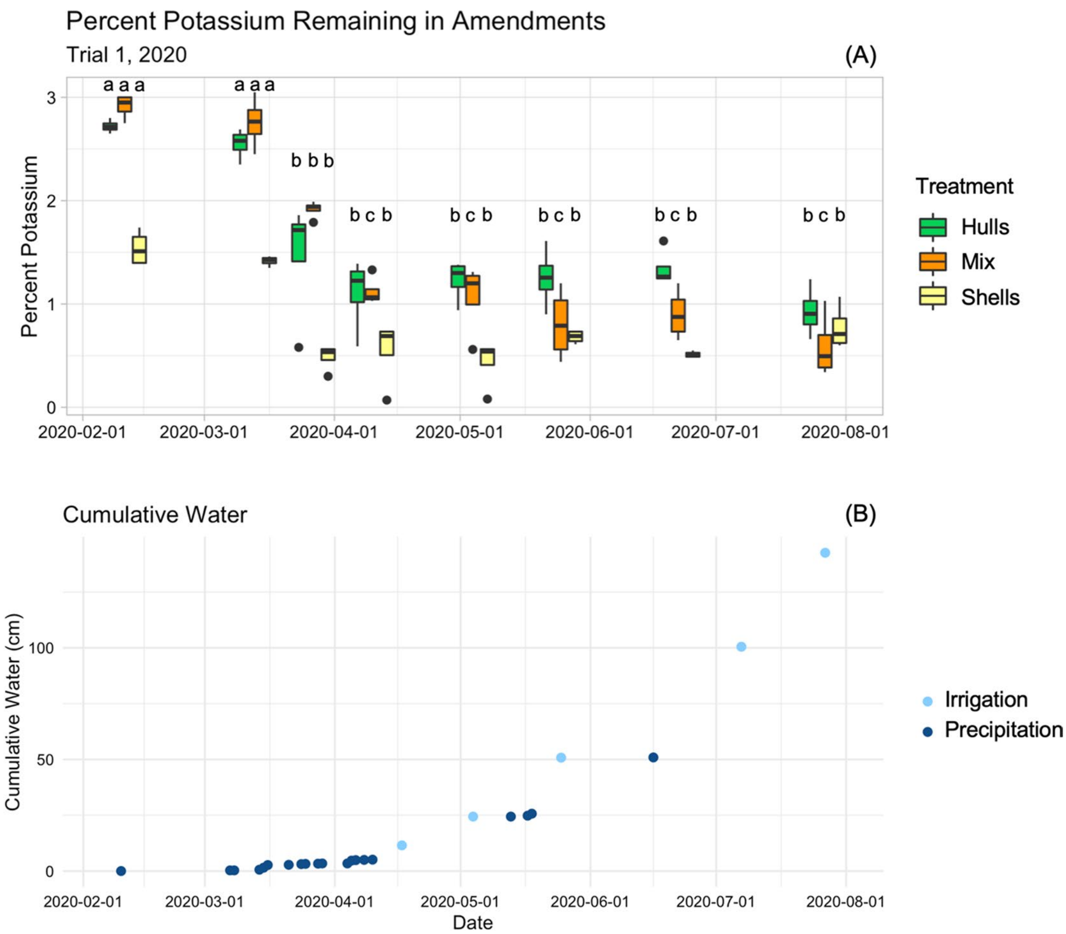

Fig. 2 Changes in K concentrations in three types of amendments (panel A), and cumulative irrigation and rainfall in the irrigated zone (panel B) from amendment application (2/10/2020) until harvest (8/10/2020) at Trial 1. Potassium concentration letter groupings represent significant differences in K concentrations over time within each separate amendment treatment type. In panel B, each point represents a water event that added to cumulative total water in the irrigated zone

hull/shell amendments fell from 1.53% K to 0.34% K while compost fell from 1.78% K to 0.70% K. While both followed a relatively similar release curve as amendments at Trial 1, the fresh hull/shell amendment released a larger fraction of total stored K than the composted hull/shell amendment.

Several models were compared to describe the observed changes in amendment K concentration as a function of cumulative water applied using Trial 1 data from February-June 2020. The most parsimonious model was a nonlinear model with a defined formula for exponential decline with vertical offset where Y0 represented the y-intercept, B0 was a parameter that regulated change in steepness of the curve, and C0 was the height at which amendment K concentration ended:

$$Amendment[K] \sim Y0 * \exp(B0 * cumulative\ water) + C0 \quad (2)$$

This model can be used to help predict K release from amendments based on cumulative applied water. A steep decline in K concentration occurred for all three materials in the first 13 cm of applied water, after which K concentration plateaued (Fig. 4). As no K fertilizer was applied during the time frame of the Trial 1 data used for this model, this model was most appropriate for orchards where additional K sources were not applied after hull/shell application.

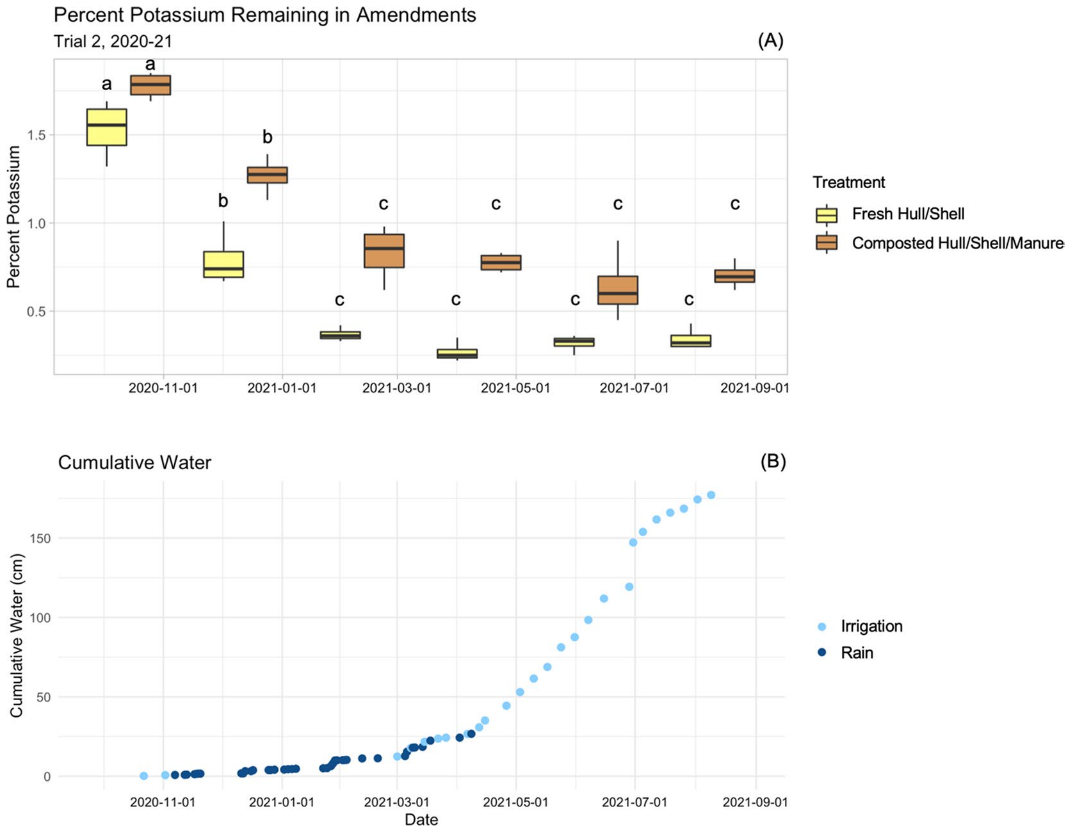

Fig. 3 Changes in K concentrations in fresh hull/shell and composted hull/shell/manure amendments on the soil surface (panel A) and cumulative irrigation and rainfall in the irrigated zone (panel B) over time at Trial 2. Letter groupings in panel A represent significant differences in K concentration over time within each separate amendment

However, for comparison this model was utilized with data from the fresh vs. composted hull/shell amendments in Trial 2 where low rates of K fertilizers were applied, which may be reflected in the more gradual K release curve (Fig. 4).

At Trial 3, the hull/shell mix maintained over time with off-ground harvest declined by approximately 95% of initial K concentration under 478 cm (188 in) of cumulative water after one year (Fig. 5). Off ground harvest enabled this extended period beyond harvest in August and hull/shells remained undisturbed. After application in October 2020, the hull/shell layer K concentration dropped dramatically with the first 25.4 cm (10 in) of water within the wetted zone in the first month. Then in mid-November, 4.5 metric tonnes ha^{-1} (2 US tons ac^{-1}) of compost were applied across the entire orchard, which led to an increase in hull/shell amendment layer K concentration when sampled in early December. In early February, after 36 cm of cumulative water, hull/shell K had dropped substantially again. In early March 2021, approximately 14 kg ha^{-1} (12.5 lb ac^{-1}) K fertilizer was applied through irrigation and hull/shell amendment layer K concentration increased again slightly. Finally, from June onward, hull/shell K concentration remained at approximately 0.1% K despite ongoing K fertigation and irrigation events.

Release to the soil XK pool over time

At Trial 1, soil XK in the top 0–10 cm soil was significantly impacted by amendment treatments (A $p < 0.001$), date (D $p < 0.001$), and treatments resulted in different soil XK trends over time (A x D $p < 0.01$). Soil XK was significantly higher in all hull/shell amended treatments compared to the bare soil control (no amendments) within 1–2 months after application in February and November 2020

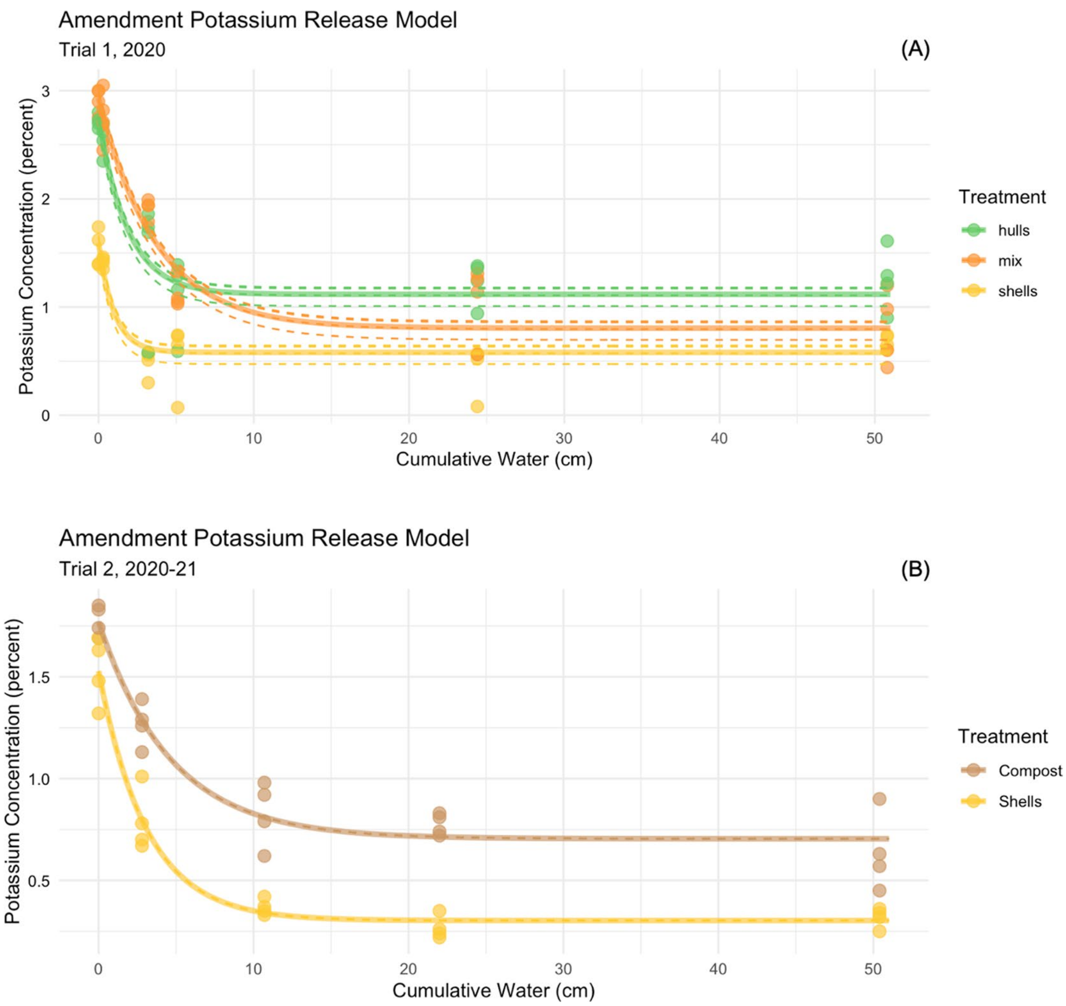

Fig. 4 A nonlinear model with a defined formula (Eq. 2.) for exponential decline with vertical offset was most appropriate for predicting average K concentration as a function of cumulative water applied (irrigation and rainfall in the irrigated zone) for amendments applied at Trial 1 (panel A) and Trial 2 (panel B). Cumulative water integrated irrigation records with rainfall data, as described in methods. No potassium fertilizer was applied at Trial 1, while 10 split applications of potassium fertilizer were applied at Trial 2 within the time frame captured in the above figure B. Potassium fertilizer applications may help explain the more gradual decline in K concentration at Trial 2 compared to Trial 1. Dashed lines represent confidence intervals

(Fig. 6). This occurred after approximately 7 weeks and 3.18 cm (1.25 in) of cumulative water in the form of rainfall following the February application (irrigation had not yet begun). All hull/shell amendment treatments maintained higher average soil XK than the bare soil control from that time onward, though not always significantly different. In October 2020 prior to amendment application in November, amended soils maintained higher average soil XK compared to the control, though only the soil amended with the hull/shell mix was statistically significant. After application in November 2020, soils under hulls, mix, and shells had significantly higher XK than control soil in January 2021. In October 2021, soils under all three amendments maintained higher average XK compared to control (unamended bare soil), with significant differences for hull and shell treatments.

At Trial 2, soil XK in the top 0–10 cm soil was significantly impacted by amendment treatments (A

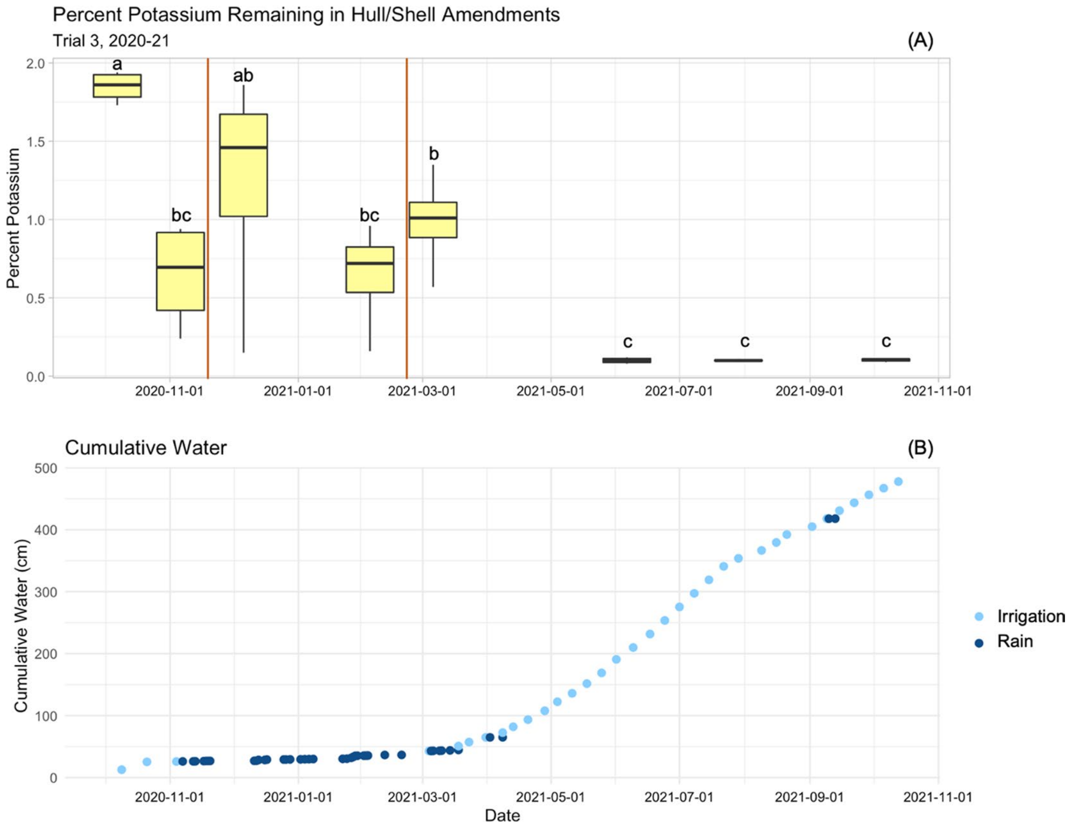

Fig. 5 Changes in K concentrations in the hull/shell mix maintained over time with off-ground harvest (panel A) and cumulative irrigation and rainfall in the irrigated zone (panel B) at Trial 3. Orange vertical lines in panel A represent a compost application across the entire orchard in mid-November 2020, and a K fertigation event in early March 2021. Off-ground harvest was implemented in early August 2021 which maintained the organic layer and enabled a longer-term assessment of hull/shell K. Letter groupings represent significant differences in the hull/shell mix K concentration between different sampling times

$p < 0.001$), date (D $p < 0.001$), and treatments resulted in different soil XK trends over time (A x D $p < 0.001$). After amendment application in mid-October 2020, amended soils had higher average XK in the upper 0–10 cm than control soils in late October onward, becoming statistically significant at late November after approximately 1.5 cm (0.6 in) of cumulative water (Fig. 7). Soil XK tended to be highest under the shell treatment. After a year, average soil XK was higher in both amended soils compared to the control, though only shell amended soil was statistically significantly higher. Potassium thiosulfate fertilizer was applied uniformly across the orchard at 149 kg ha^{-1} (133 lb ac^{-1}) K total from 3/1/2021 until 6/15/2021 through 16 split applications, which may help explain the increase in soil XK in all treatments at 5/11/2021.

At Trial 3, soil XK in the top 0–10 cm soil was significantly impacted by amendment treatments (A $p < 0.001$), date (D $p < 0.001$), but treatments did not result in different soil XK trends over time. The hull/shell mix applied in October 2020 led to significantly higher soil XK in the upper 0–10 cm compared to bare control soil after 16 days and approximately 25.4 cm (10 in) of irrigation water (Fig. 8). The hull/shell mix maintained significantly higher average soil XK than the unamended bare control soil during January-May 2021. Approximately 131 kg ha^{-1} (117 lb ac^{-1}) K fertilizer was applied uniformly through irrigation in six applications between 5/6/2021 and 7/27/2021, which may help explain the increase in soil XK in both treatments during this time. After one year, prior to the second fall application, soil XK was

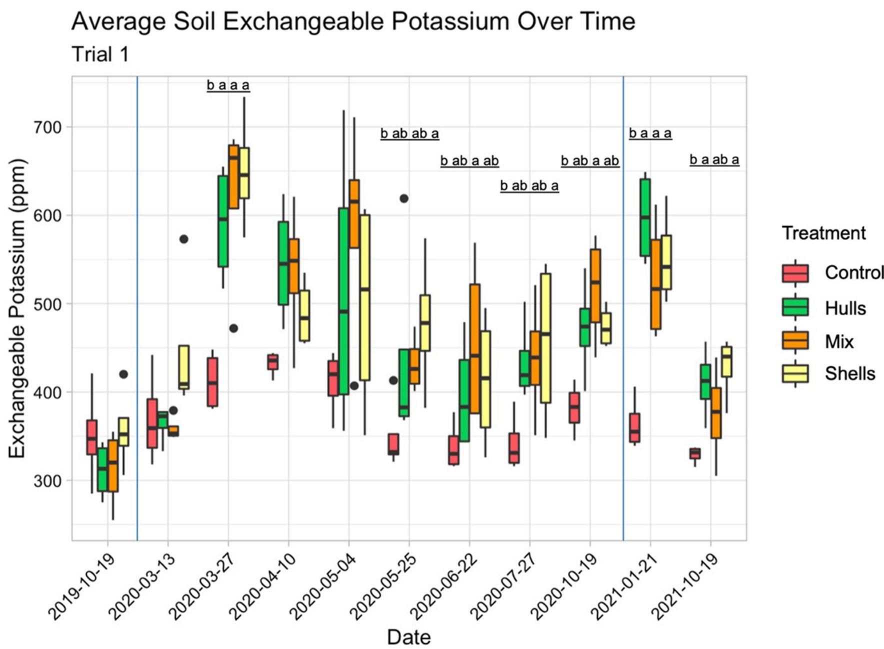

Fig. 6 Average soil XK in the top 0–10 cm under treatments across time at Trial 1. Blue lines indicate hull/shell amendment applications on 2/10/2020 and 11/12/2020. Letter groupings indicate significant differences between treatments within each date. For time points with no letters, treatments were not significantly different. All soil XK data from Trial 1 are included in this figure to highlight the finding that higher soil XK was maintained under hulls, mix, and shells compared to the control within each time point (sometimes statistically significant, sometimes not)—note that the dates on the x-axis are not uniformly spaced over time

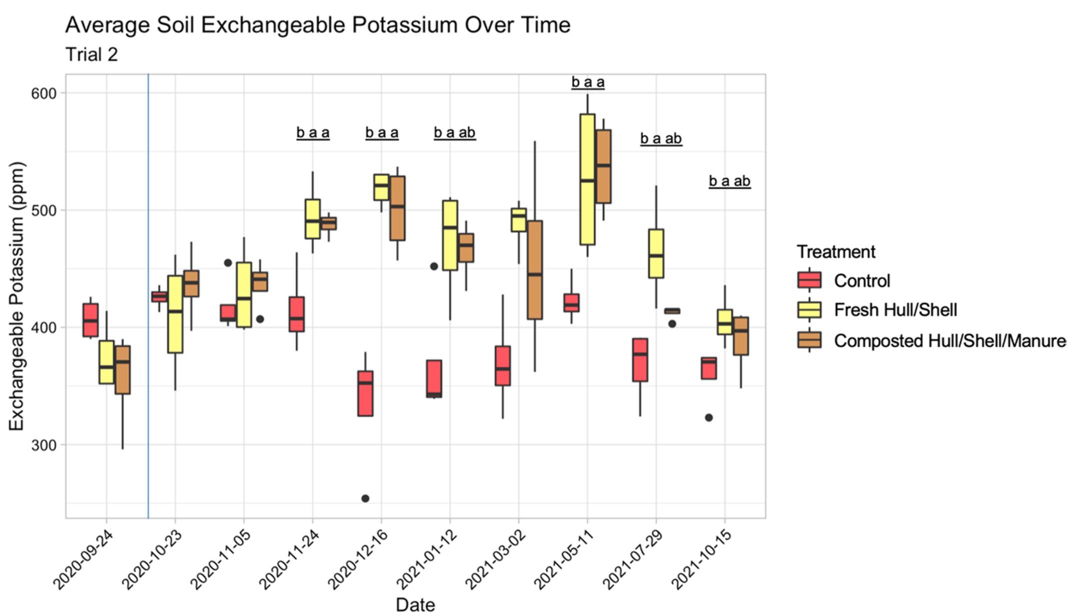

Fig. 7 Average soil XK over time across all treatments at Trial 2 in the upper 0–10 cm soil. The blue line represents the first amendment application on 10/14/2020. Soil XK became statistically significantly higher under shells and compost on 11/24/2020. Letter groupings indicate significant differences between treatments within each time point. For time points with no letters, treatments were not significantly different. All soil XK data from Trial 2 are included in this figure to highlight the finding that relatively higher soil XK was maintained under both fresh and composted hull/shell materials compared to the control within each time point (sometimes statistically significant, sometimes not)—note that the dates on the x-axis are not uniformly spaced over time

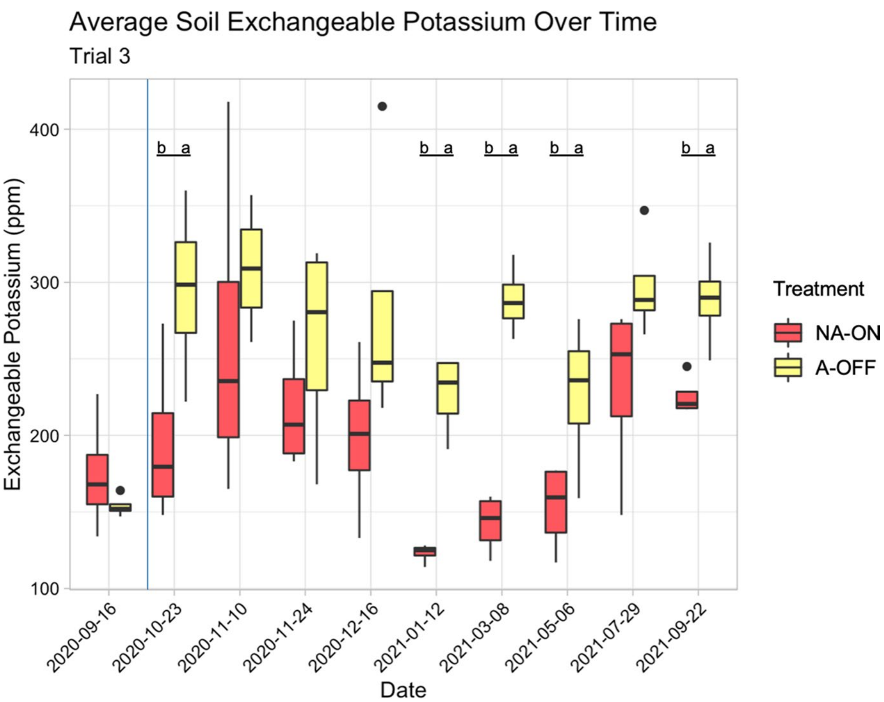

Fig. 8 Soil XK at Trial 3 in the upper 0–10 cm soil over time in NA-ON (No Amendments, On Ground Harvest) and A-OFF (Amendments, Off Ground Harvest). The blue line represents the hull/shell amendment applied on 10/7/2020. Off ground harvest was implemented in early August 2021 which ensured the amendment layer remained undisturbed. Letter groupings indicate significant differences between treatments within each time point. For time points with no letters, treatments were not significantly different. Soil XK data from all time points are included in this figure to highlight the finding that higher soil XK was maintained under the hull/shell amendment compared to the control at each date sampled (sometimes statistically significant, sometimes not)—note that dates on the x-axis are not uniformly spaced over time

significantly higher under the amendment compared to control soil.

The upper 0–10 cm of soil was the focus sampling depth because the hull/shell amendment was surface-applied, K typically moves slowly through the soil, research questions were focused on K release dynamics, and almond tree roots are concentrated in upper soil layers to access water and nutrients. However, deeper soil samples indicated that soils with hull and shell amendments occasionally (though inconsistently) contained higher soil XK concentrations than respective control soils at each trial. At Trial 1, soil amended with the hull/shell mix had significantly higher soil XK than the control soil at the 20–30 cm depth in the fall of 2021 (data not presented). At Trial 2 and Trial 3, in early March 2021 soil XK was significantly higher under the hull/shell mix than the respective controls at 10–20 cm depth.

Amendment decomposition

At Trial 1, percent total decomposition from application in November 2020 to late July 2021 was highest for hulls (38% of initial dry weight remained) while mix and shells were statistically similar (approximately 54% remained). The shells and mix decomposed by approximately half of initial dry weight, while hulls decomposed by approximately two thirds (Table 2). Treatment, length of time in the field, and the interaction of treatment and time all significantly ($p < 0.001$) affected net mass remaining.

At Trial 2, the percent net dry mass remaining of the amendment applied the prior fall was 68% for fresh hull/shells and 75% for compost on 6/11/2021 (Table 2). Net dry mass remaining gradually declined for both amendments, with final average hull/shell percent net dry mass remaining slightly lower than compost. Hull/

Table 2 After fall 2020 applications, final average percent net mass remaining in litter bags in 2021 at the last collection time point for each site

Trial	Treatment	Time Length	Total Water (cm)	Initial C:N	Avg. Net Mass Remaining
1	Hulls	257 days	155.3	71:1	38%
	Hull/shell Mix (82% hull, 18% shell)			65:1	55%
	Shells			70:1	54%
2	Hull/shell Mix (5% hull, 95% shell)	240 days	98.4	91:1	68%
	Hull/shell-based Compost			24:1	75%
3	Hull/shell Mix (32% hull, 68% shell)	365 days	477.7	52:1	45%

Estimated total water represents cumulative rainfall and irrigation in the wetted zone on an area basis. All values are dry weight

shell net mass declined slightly more linearly than composted hull/shell net mass (Fig. 9a). Considering all time points together, ANOVA indicated length of time in the field significantly ($p<0.001$) reduced net dry mass remaining for both shells and compost materials, while differences between fresh vs. composted hull/shell materials were marginally significantly different ($p=0.056$). At Trial 3, the net mass remaining of the hull/shell mix declined linearly (Fig. 9b) with approximately 45% remaining after one year (Table 2). Length of time led to significant ($p<0.001$) reductions in net dry mass remaining at Trial 3 as well.

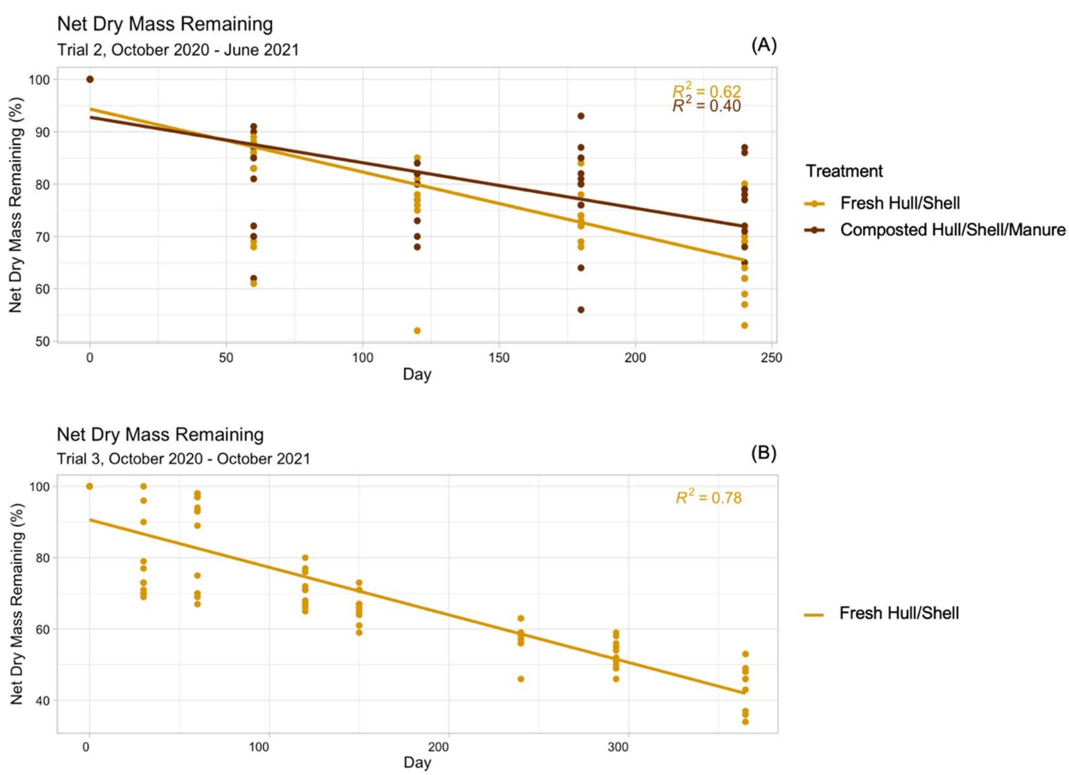

Fig. 9 Decomposition of amendments expressed as percent net dry mass remaining at Trial 2 (panel A) and Trial 3 amendments that were maintained over time with off-ground harvest (panel B), 2020–2021. Decomposition by mass loss within the irrigated zone was generally linear over time

July leaf nutrients and yield

At Trial 1, considering all three years together, significant effects were found for treatment, year, and the interaction of treatment and year for leaf Mg, but only the latter two for leaf K, suggesting leaf K was particularly influenced by year at this trial (Supplementary Table 5). In July 2020 five months after the first application, the control trees had significantly higher leaf K than trees amended with the mix and shells (Supplementary Table 6). However, all treatments had sufficient K based on recommendations for July almond leaf tissue samples which should fall within the 1.4–2.0% K range (Micke 1996). In July 2021, leaf K averages were slightly higher in trees amended with hulls, mix, and shells, though not statistically significant. In July 2022, leaf K was significantly higher and Mg was significantly lower in hulls, mix, shells, and potassium sulfate treatments compared to the control. This tradeoff between K and Mg suggests competitive nutrient uptake favoring K after two years and two applications, however averages for both nutrients remained within sufficiency ranges in all treatments (Figs. 10a and b) (Micke 1996).

At Trial 2, no significant differences in leaf K were found between treatments in July 2021 or 2022 (Table 3). In both years, average leaf K in trees amended with shells and compost were slightly higher than control trees, though not significant. The significant reductions in leaf Mg under amendments observed at the other field trials was not observed at Trial 2. However, considering all data together from all treatments, an inverse relationship between leaf K and leaf Mg was observed at all three sites (Fig. 11). When analyzing both years together, ANOVA indicated that only year significantly affected leaf K at Trial 2. There

Table 3 Average values for July leaf nutrients sampled on 7/13/2021 and 7/14/2022, Trial 2

Treatment	July 2021		July 2022	
	K (%)	Mg (%)	K (%)	Mg (%)
Control	2.05	0.89	2.75	0.86
Shells	2.16	0.89	2.91	0.90
Compost	2.19	0.90	2.90	0.90

No significant differences were found between treatments within each year for the given nutrients

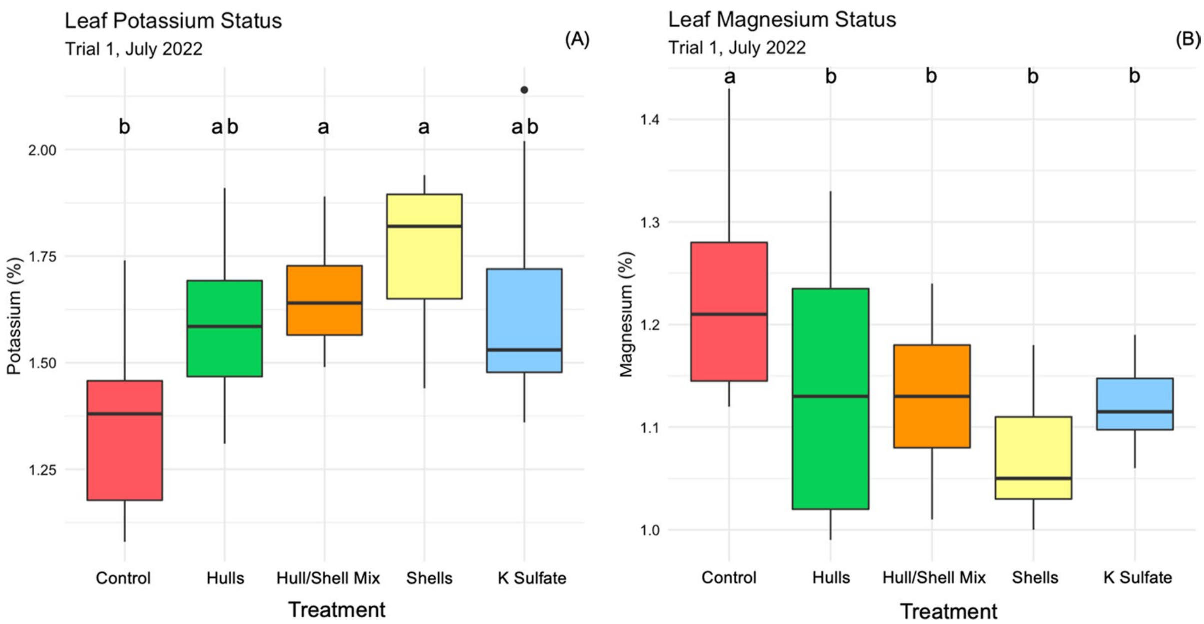

Fig. 10 Average July leaf potassium (panel A) and magnesium (panel B) status for each treatment at Trial 1, July 2022. Letters indicate significant differences between treatments within each nutrient. High K applications through amendments led to a tradeoff between tree uptake of K and Mg after two years and two applications

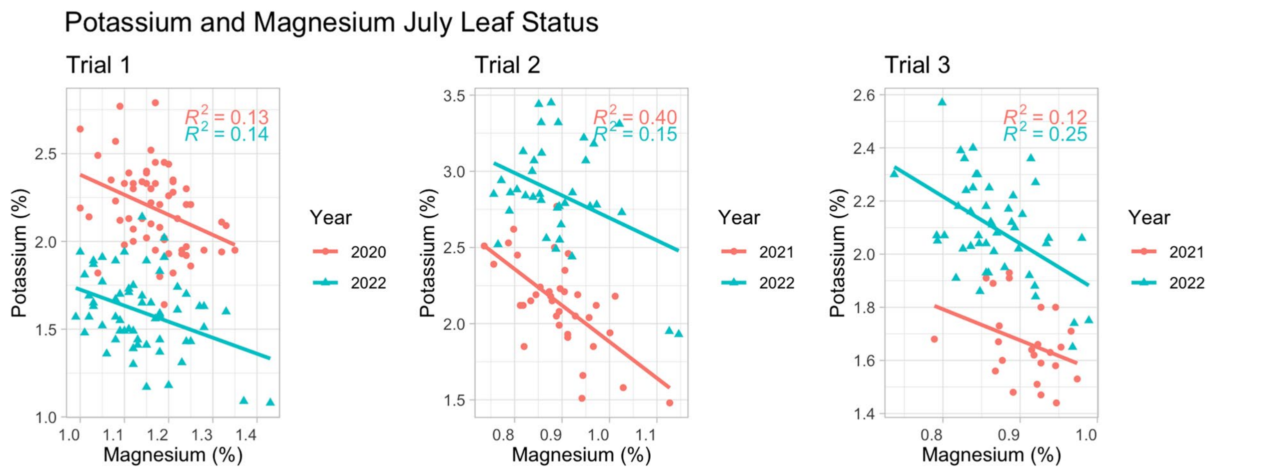

Fig. 11 Correlations between July leaf K and Mg across years and sites, including all data from all treatments. While competition between K and Mg only led to significantly lower Mg levels under hull/shell amended trees at Trial 1 and Trial 3, the inverse relationship was observed at all trials

were no significant effects of treatment, year, and their interaction on leaf Mg (Supplementary Table 5).

At Trial 3, amended tree leaf K was significantly higher and leaf Mg was significantly lower compared to control trees in July 2021 (Table 4). In July 2022, leaf K was higher in both amended treatments than unamended treatments, significantly greater than the control for the amended off ground harvest trees only. In both years, increases in leaf K and decreases in Mg suggest competition between K and Mg (Fig. 11). However, average Mg and K levels in all treatments were within the respective recommended ranges for almond. Considering leaf data from both years, treatment and year significantly affected leaf K and Mg, but no effects were found for the interaction of treatment and year at this trial (Supplementary Table 5). For all trials, tree K status was within sufficient range suggesting K status did not limit yield.

No yield differences between treatments were found at any of the trials. Year had a significant ($p < 0.001$) effect on yield at Trial 2 only (Supplementary Table 8). While significantly greater percentages of leftover amendments were occasionally found in the yield debris of some amended treatments at Trial 1 and Trial 2 (ranging from 0.1–12% of total debris dry weight), the growers/processors reported hull/shell debris was negligible and did not cause any processing issues. At Trial 1, the shell treatment debris contained lower percentages of leftover amendments likely due to the lower weight and smaller size of shells that filtered out during mechanical pickup. At Trial 3, the catch frame harvest equipment led to significantly lower total debris in yield samples compared to the two on ground harvest treatments (Supplementary Table 9).

Table 4 Average values for July leaf nutrients sampled on 7/15/2021 and 7/14/2022 at Trial 3

Treatment	July 2021		July 2022	
	K (%)	Mg (%)	K (%)	Mg (%)
(1) NA-ON (Control: No Amendments, On Ground Harvest)	1.59 b	0.93 a	2.02 bc	0.898 a
(2) NA-OFF (No Amendments, Off Ground Harvest)	–	–	1.96 c	0.895 ab
(3) A-ON (Amendments, On Ground Harvest)	–	–	2.18 ab	0.842 bc
(4) A-OFF (Amendments, Off Ground Harvest)	1.74 a	0.88 b	2.22 a	0.837 c

Letters indicate averages that are significantly different between treatments within the given year and nutrient. In July 2021 the harvest treatments had not yet been implemented, thus leaf samples were taken to compare the effects of the hull/shell amendment with the control within the short time span between fall application and the first following summer prior to harvest

Discussion

Amendments released potassium and increased soil XK

At all sites, K solubilization from hulls, mix, shells, and mix-based compost exhibited rapid initial K release followed by a more gradual release stage or plateau, a pattern that has been observed in prior residue studies (Dong et al. 2019; Tagliavini et al. 2007; Li et al. 2014; Rodríguez-Lizana et al. 2010). The rapid initial K solubilization phase was not initially limited by the relatively high C:N ratio of fresh hull/shell materials, which aligns with the literature. The remaining fraction of residue K was released more gradually over time, as complex plant structural components such as cellulose, hemicellulose, and lignin decomposed (Rosolem et al. 2005; Cobo et al. 2002). Composted and fresh hull/shell materials displayed a similar K release pattern despite different initial C:N ratios. Data from these field trials illustrate that within the first year after application, K concentration in hull/shell amendments was negatively correlated with cumulative water and time while positively correlated with decomposition and C:N ratio at Trial 1 and Trial 3 where only fresh hull/shell materials were tested (Fig. 12). In other words, as water and time increased, amendment K concentration, net mass remaining, and C:N ratio of fresh hull/shell amendments declined. Meanwhile at Trial 2, the C:N ratio of the composted hull/shell materials remained relatively stable over time compared to fresh hull/shell materials.

Biological decomposition processes assisted in plant cell lysis and K release over time. However, since decomposition data is not readily available for growers, utilizing cumulative water applied from irrigation and rainfall records presents a practical tool for growers and researchers to understand and predict K release from hull/shell amendments in the short-term through solubilization. The amendment K model using Trial 1 data illustrates K release as a function of water applied in systems without additional K fertilizer, while the model using Trial 2 data shows a more gradual K decline likely due to the effects of low-rate K fertigation events. However, alternate models for K release may be needed where high K applications are made through fertilizers and other amendments in addition to hull/shell amendments. At Trial 3, hull/shell K concentrations temporarily increased following K fertilizer and compost additions, suggesting that the amendment can temporarily retain applied K before releasing it into the soil. Plant residues have been shown to adsorb K during decomposition and re-release stored K later in the season; nutshells such as almond and pecan have high lignin content and functional groups that favor cation adsorption (Andrews et al. 2021). This capacity to retain and re-release K did not persist beyond approximately 43 cm of cumulative water after hull/shell application (5 months) at Trial 3, despite ongoing K fertilizer applications.

Applying hull/shell amendments prior to winter rains maximized K release. Fall application enabled greater total K solubilization at Trial 1 due to higher cumulative water compared to the

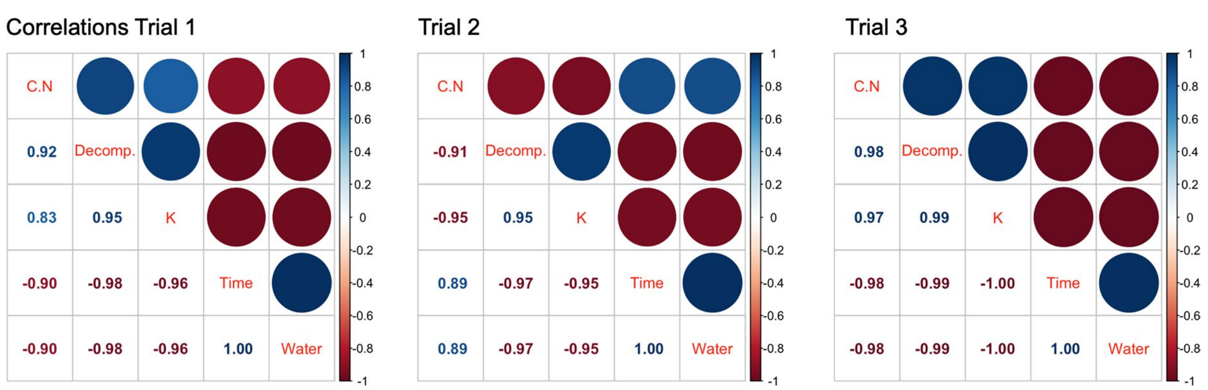

Fig. 12 Correlations between K remaining (percent), time (number of days), cumulative water (cm), C:N ratio, and decomposition (percent remaining) using initial and final litter bag data from all trials. Trial 1 final data was collected at 258 days after application, Trial 2 final data at 240 days, and Trial 3 data at 365 days

Table 5 Soil XK changes and amendment K concentration changes from all sites

Trial	Treatment	Soil XK Changes		Amendment %K Changes			
		Shortest Time to Increase Soil XK	Water Applied (cm)	Initial & Final Dates	Initial %K	Final %K	Water Applied (cm)
1	Hulls	46 days	3.2	2/10/20—7/27/20	2.72	0.93	143
1	Hulls	–	–	11/12/20—6/26/21	2.07	0.68	553
1	Hull/shell Mix	46 days	3.2	2/10/20—7/27/20	2.91	0.59	143
1	Hull/shell Mix	–	–	11/12/20—6/26/21	2.23	0.76	155
2	Hull/shell Mix	41 days	1.6	10/14/20—6/11/21	1.53	0.34	98.4
3	Hull/shell Mix	16 days	25.4	10/7/20—10/7/21	1.84	0.09	478
1	Shells	46 days	3.2	2/10/20—7/27/20	1.54	0.77	143
1	Shells	–	–	11/12/20—6/26/21	1.85	0.77	155
2	Compost Mix	41 days	1.6	10/14/20—6/11/21	1.78	0.70	98.4

The Soil XK Changes columns show the shortest length of time before significant increases soil XK were observed in the upper 0–10 cm soil and corresponding water applied. The Amendment %K Changes columns show initial and final %K and corresponding water applied. All Final %K averages were significantly lower than their corresponding initial %K average within each trial and time frame. Trials 1, 2, and 3 were on clay, silty clay loam, and loam soil, respectively. Trials 1 and 2 were drip irrigated whereas Trial 3 was micro sprinkler irrigated. This table represents soil, amendment, and water dynamics within the irrigation wetted zone

previous mid-winter application (Table 5). Significant decreases in hull/shell amendment K concentrations occurred under approximately 3.3–25.4 cm (1.3–10 in) of cumulative water in the short term, while maintaining the amendment layer with off ground harvest enabled a 95% reduction in total K concentration after one year. These findings align with prior studies showing that high K release rates from tree crop residues can occur under high water applications, such as 90% K solubilized from coffee residues under approximately 30 mm of weekly simulated rainfall for 40 weeks (Zoca et al. 2014) and 92% total K from decomposing cacao husks saturated with water for 48 h (Hougni et al. 2021).

At all sites, soil XK in the upper 0–10 cm of soil significantly increased under all amendments within approximately the first 2–7 weeks (3.3–25.4 cm of water in the irrigation wetted zone) across different soil types and irrigation systems. After the first amendment application, average soil XK in the upper 0–10 cm remained higher under all hull/shell amendments compared to control soils through the following fall, statistically significant only in some cases. Treatment and Date both significantly affected soil XK at all three sites.

In general, K moves relatively slowly through the soil profile, unless in sandy soil or under excessive water applications, and likely remained within the almond root zone in these soils. Occasionally, hull/shell amended soils at depths below 10 cm were found to have higher soil XK than control soils, though inconsistent. At all sites, soil XK levels in the upper 0–20 cm soil were above the sufficiency range for almond orchards (Supplementary Table 10). Hull/shell amendments led to significantly higher soil XK despite high pre-existing levels at Trial 2. In California almond orchards, fertilizer K is often banded in almond orchards whereas hull/shell amendments provide K inputs across the soil surface, which may offer an advantage for root K uptake. In both cases, water is required to solubilize applied K into the soil where plant roots take up K in the monovalent cation form (K^+).

Amendments decomposed over time

Hull/shell amendment decomposition followed a relatively linear decline in net mass remaining. The off ground harvest treatment enabled longer-term decomposition data collection that indicated the hull/shell mix within the irrigation zone decomposed by approximately half of its initial dry mass after one year. While high plant residue C:N ratios tend to be linked with slower decomposition over time (Dong et al. 2019; Li et al. 2014), additional hull/shell characteristics may influence decomposition rate. For instance, amendments applied in the fall of 2020 at Trial 1 had relatively similar initial C:N ratios (65:1—71:1), yet total decomposition was significantly higher for hulls than the mix and shells. Almond hulls contain bioactive compounds such as high sugar content, with approximately 18–30% soluble sugars by dry weight (Prgomet et al. 2017; Aguilar et al. 1984; Esfahlan et al. 2010). This suggests hulls could support a microbial community that includes decomposers, which may explain the observed greater net decomposition.

At Trial 2, the hull/shell/manure compost had lower net decomposition than the fresh hull/shell mix. The composted material had a lower initial C:N ratio which can be attributed to the nitrogen additions from manure prior to composting. This amendment had already undergone substantial microbial transformations during the composting process prior to application, leaving materials with more recalcitrant components to be applied in the field. In contrast, the fresh hull/shell mix began the decomposition process in the field and likely contained more simple C compounds that were readily accessible by decomposers.

Amendments improved tree K status without influencing yield

Applying the hull/shell amendments in the fall increased soil XK during the following spring when almond tree nutrient uptake commenced. This coupling of K supply with the timing of annual tree K demand suggests that hull/shell amendments can serve the same function as K fertilizer. The rate of K application should be based on expected yield, tree K status, and soil K contribution with the goal of matching K applied to K exported from the crop system at harvest (Muhammad et al. 2018). Muhammad et al. 2018 found that different K fertilizer sources had no effect on leaf K concentration or yield, suggesting K from all sources were equally available. Regardless of source, plants take up K as the monovalent cation. Almond hulls/shells can be used as a K-rich organic matter amendment that can release K, increase soil XK, and improve leaf K status, thus replenishing crop system K levels. Rather than exporting K in these fruit tissues from the orchard, this practice provides an opportunity to recycle a large fraction of stored plant K annually to help meet tree K demand. This K recycling practice can be used within a nutrient budget approach to reduce reliance on mineral K fertilizers and retain K within the crop system.

The degree to which hull/shell amendments may increase July leaf K status was likely influenced by the year and site-specific factors such as pre-existing plant and soil K status, amendment rate, soil type, and irrigation and fertilizer practices. Prior to trial establishment, soil XK levels were high at Trials 1 and 2, all leaf K status was sufficient in 2021, and increases in soil XK under amendments did not significantly affect July tree leaf values that year. However, initial soil XK and leaf K status were lower at Trial 3. This room for improvement, the high application rate, and site-specific factors could help explain the significantly higher leaf K under the hull/shell amendment within only one year at Trial 3. While few prior studies have investigated how nutshell amendments affect mature tree leaf K, previous studies found increased leaf K levels of young seedlings in potting media. Blended coffee husk amendments incorporated into nursery soil substrate at three rates significantly increased cashew seedling leaf K after 20 weeks (Nduka et al. 2015). Similarly, cashew seedlings grown in soil substrates with incorporated cacao husk amendments increased seedling leaf K after 16 weeks and were proposed as a replacement for inorganic K fertilizer (Agele and Agbona 2008).

While leaf K and Mg status fell within sufficiency ranges at all sites, these nutrients were inversely correlated to varying degrees based on site and year. This tradeoff between significant increases in leaf K and significant reductions in leaf Mg occurred under hull/shell amendments at two of the three trials. Since competitive uptake has been shown to occur between K and Mg when K is supplied at excessive rates, soil cation balance and leaf tissue analyses can help growers monitor this dynamic and prevent Mg deficiency (Xie et al. 2021).

These field trials occurred at relatively high-input, intensive commercial almond orchards where initial leaf K values were sufficient before trial establishment. Yield effects would be more likely to occur in orchard environments where yield is limited by factors that hull/shell amendments can improve. Prior studies that found yields increased under nutshell amendments have most often attributed yield effects to increased soil water content and nutrient uptake (Andrews et al. 2021). For instance, Jafari et al.

(2012) found that almond shell mulch led to higher yields and fruit quality in a rainfed water-limited fig orchard. Macadamia husk mulch was found to increase macadamia yield and foliar K levels (Nagao et al. 1992; Lobel et al. 1994). Cacao husk amendments have been shown to increase cacao seedling growth (Oyewole et al. 2012). The effects of nutshell residues on leaf nutrients, growth parameters, and yield may be most apparent in seedlings, low-input systems, and K-deficient orchards.

The small size and light weight of the hull/shell materials (particularly shells) allowed them to largely filter out during mechanical on ground pick up. Utilizing catch frame harvest in 2022 at Trial 3 led to significantly lower debris in yield samples (1–2% total dry debris) than on ground harvest (8–15% total dry debris), indicating that off ground harvest equipment can lead to cleaner yield in both amended and unamended plots. This demonstrates that off ground harvest equipment in almond systems can reduce soil disturbance, preserve the organic layer on the soil surface, and produce cleaner yield samples regardless of whether the soil is bare or amended.

Implementation

Hull/shell amendment K increased soil XK and tree K status, achieving the same goals as traditional K fertilizer products that are applied to raise depleted soil XK levels and ensure sufficient almond K status for optimum plant function and productivity (Reidel et al. 2001, 2004). This practice can assist growers in reducing reliance on external K fertilizer inputs which are relatively high for California almond systems (Sumner et al. 2019). Growers can supplement or substitute a portion of inorganic K fertilizer with K supplied from hull/shell amendments. This practice could be impactful in low-input systems, where fertilizer is expensive, or where agricultural soil has been depleted of K over time. All collaborating growers expressed interest in replacing a portion of fertilizer K with hull/shell amendment K in the future based on the results of this research.

In K deficient orchards, the application rate can be designed to help correct low soil XK levels and bring plant K status into a safe range. Sampling to monitor soil XK and leaf K levels can help guide annual application rates. Once sufficient K status is observed, the hull/shell application rate can be adjusted to maintain optimum soil and plant K levels while avoiding excessive K inputs that could lead to Mg deficiencies. Using the nutrient budget approach, hull/shell amendments can be applied at a rate that matches K export from a given orchard. A hull/shell mix with a high proportion of hulls will likely have a higher K concentration than a predominately shell-based mix. Since processors aggregate hull/shell materials from many different almond orchards, achieving consistent and precise annual K application rates through amendments can be challenging. If a high degree of precision is needed, stockpiled materials can be analyzed for K concentration prior to application. This could help growers and researchers tailor amendment application rates toward target K rates. Otherwise, samples of applied materials can be used for estimates of hull/shell K application rates in retrospect.

Applying hulls and shells as amendments offers a strategy to assist the almond industry in working toward the established 2025 goals of zero waste and reduced harvest dust (Almond Board of California 2019). This recycling practice benefits processors by providing a convenient outlet to relocate excess crop residue promptly out of processing facilities, creating space for incoming materials. Growers at Trial 1 previously applied surplus hull and shell materials as mulch along roadsides and in orchard alleys to enable machinery to access fields after rain and reduce dust in the summer. Processors expressed the need to move these materials out of the processing facility promptly and reduce the risk of mulch fires. Hull/shell amendments could complement other almond biomass recycling strategies that provide crop system benefits, such as whole orchard recycling (Jahanzad et al. 2020, 2022). Off ground harvest equipment eliminates the sweeping step at harvest which produces dust. Off ground equipment such as catch frames require appropriate engineering adjustments to almond orchard specifications (e.g., tree spacing, scaffold branch height) to avoid trunk damage and ensure the crop is funneled effectively out of the tree row into the alley.

Further research is needed to assess the effects of integrating hull/shell amendments with other agroecosystem-oriented nutrient management practices that can help match nutrient supply with crop demand. For instance, growing evidence supports the use of cover crops, reduced soil disturbances, and livestock integration in almond orchards (Fenster et al. 2021; Soto et al. 2021; Martinez-Mena et al. 2020). Minimizing orchard soil surface disturbance can promote an organic layer on the soil surface in orchard systems, which can enhance nutrient cycling and availability (Andrews et al. 2021). Off ground harvest preserves the hull/shell layer, enabling more complete K solubilization while building an organic layer on the orchard soil. This undisturbed organic layer can be managed to optimize nutrient cycling benefits provided by organic matter such as leaf litterfall, hull/shell materials, shredded pruning mulch, cover crop residues, compost, and other regionally available organic materials. Long-term trials are needed to examine effects of hull/shell amendments on tree nutrient status, water management, tree physiology, soil microbial responses, soil fertility, and soil structure.

Conclusion

These field trials provide strong evidence that almond hulls and shells are viable materials that can be used as K-rich organic matter amendments applied on orchard soils. Almond hull/shell amendments rapidly solubilize K under water application, increase soil exchangeable K levels, and increase tree leaf K status to varying degrees within the first 1–3 years. Growers can tailor amendment application rates based on the target leaf K and soil XK levels. For orchards with sufficient K status, this practice can be used to maintain K by replacing the estimated amount of K exported at harvest. While no tree Mg deficiencies were found in these trials, high K inputs through hull/shell amendments may occasionally compete with Mg. Decomposition rates of fresh hull/shell amendments were relatively linear and total decomposition was higher for hulls than shells. While fresh and composted hull/shell materials began with different initial C:N ratios, they displayed similar K release patterns and both significantly increased soil XK. Total hull/shell K release and total decomposition can be maximized by using off ground harvest to maintain the amendment layer over time, rather than disturbing it with on ground harvest. This organic matter amendment presents an opportunity to recycle hull/shell K, increase soil and plant K status, and reduce reliance on K fertilizers.

Acknowledgements Thank you, Dr. E.A. Laca, for guidance with model development and statistical analyses.

Author contributions Conceptualization and funding acquisition: EMA, SDSK, PHB, ACMG. Experimental Design: EMA, SDSK, PHB. Investigation: EMA, DR. Data analysis and visualization: EMA. Writing: EMA. Editing: EMA, DG, ACMG, SDSK, PHB.

Funding This research was funded by the Western Sustainable Agriculture Research and Education Grant, grant number SW20-912, and the Foundation for Food and Agriculture Research Seedling Solutions Program, grant number CA18-SS-0000000260.

Data Availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

Agele SO, Agbona AI (2008) Effects of cocoa pod husk amendment on soil and leaf chemical composition and growth of cashew (*Anacardium occidentale* L.) seedlings in the nursery. Am-Eurasian J Sustain Agric 2(3):219–224. https://www.researchgate.net/publication/228643425

Aguilar AA, Smith NE, Baldwin RL (1984) Nutritional value of almond hulls for dairy cows. J Dairy Sci 67(1):97–103. https://doi.org/10.3168/jds.S0022-0302(84)81271-0

Almond Board of California (2019) Committed to Continuous improvement: announcing the almond orchard 2025 goals. https://www.almonds.com/

Almond Board of California (2020) Almond Almanac. Modesto, California. Document #2020IR0296. https://www.almonds.com/sites/default/files/2020-12/2020%20Almond%20Almanac.pdf

Andrews EM, Kassama S, Smith EE, Khalsa SDS, Brown PH (2021) A review of potassium-rich crop residues used as organic matter amendments in orchard crop systems. MDPI Agriculture Special Issue, Organic Management and Productivity of Tree Crops, 11(7). https://doi.org/10.3390/agriculture11070580

Aphalo PJ (2016) Learn R ...as you learnt your mother tongue. Leanpub, Helsinki. http://leanpub.com/learnr

Bates D, Machler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67(1):1–48. https://doi.org/10.18637/jss.v067.i01

Bittenbender HC, Hue NV, Fleming K, Brown H (1998) Sustainability of organic fertilization of macadamia with macadamia husk-manure compost. Commun Soil Sci Plant Anal 29(3–4):409–419. https://doi.org/10.1080/00103629809369954

Brito O, Telles T, Schnitzer J, Gaspar G, Fatima M (2014) The influence of crop residues in vertical soil mobility of potassium. Semina: Ciências Agrárias 35:3043. https://doi.org/10.5433/1679-0359.2014v35n6p3043

Carmo DL, Lima LB, Silva CA (2016) Soil fertility and electrical conductivity affected by organic waste rates and nutrient inputs. Revista Brasileira de CIA do Solo 40. https://doi.org/10.1590/18069657rbcs20150152

Cobo JG, Barrios E, Kass DCL, Thomas RJ (2002) Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant Soil 240(2):331–342. https://www.jstor.org/stable/24121152

Dong S, Ma Z, Wang L, Yan C, Liu L, Gong Z, Cui G (2019) Decomposition and nutrient release characteristics of incorporated soybean and maize straw in Northeast China. Ekoloji 107:2119–2129. http://ekolojidergisi.com/article/decomposition-and-nutrient-release-characteristics-of-incorporated-soybean-and-maize-straw-in-5842

Doungous O, Emile M, Longue E, Nkengafac N (2018) Potentials of cocoa pod husk-based compost on Phytophthora pod rot disease suppression, soil fertility, and Theobroma cacao L. growth. Environ Sci Pollut Res 25(25):25327–25335. https://doi.org/10.1007/s11356-018-2591-0

Drinkwater LE, Snapp SSN (2007) Nutrients in agroecosystems: Rethinking the management paradigm. In: Sparks DL (ed) Advances in agronomy, vol 92. Academic Press, Cambridge, pp 163–186

Esfahlan AJ, Jamei R, Esfahlan RJ (2010) The importance of almond (*Prunus amygdalus* L.) and its by-products. Food Chem 120:349–360. https://doi.org/10.1016/j.foodchem.2009.09.063

Fenster TLD, Oikawa PY, Lundgren JG (2021) Regenerative almond production systems improve soil health, biodiversity, and profit. Front Sustain Food Syst 5:664359. https://doi.org/10.3389/fsufs.2021.664359

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biom J 50(3):346–363. https://doi.org/10.1002/bimj.200810425

Hougni DGJM, Schut AGT, Woittiez LS, Vanlauwe B, Giller KE (2021) How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching. Plant Soil 463:155–170. https://doi.org/10.1007/s11104-021-04885-1

Idowu OJ, Sanogo S, Brewer CE (2017) Short-term impacts of Pecan waste by-products on soil quality in texturally different arid soils. Commun Soil Sci Plant Anal 48(15):1781–1791. https://doi.org/10.1080/00103624.2017.1395448

Jafari M, Haghighi JAP, Zare H (2012) Mulching impact on plant growth and production of rainfed fig orchards under drought conditions. Journal of Food Agriculture and Environment: Helsinki, Finland 10(1):428–433. https://www.researchgate.net/publication/296392940_Mulching_impact_on_plant_growth_and_production_of_rainfed_fig_orchards_under_drought_conditions

Jahanzad E, Holtz BA, Zuber CA, Doll D, Brewer KM, Hogan S, Gaudin ACM (2020) Orchard recycling improves climate change adaptation and mitigation potential of almond production systems. PLoS ONE 15(3):e0229588. https://doi.org/10.1371/journal.pone.0229588

Jahanzad E, Brewer KM, Poret-Peterson AT, Culumber CM, Holtz BA, Gaudin ACM (2022) Effects of whole-orchard recycling on nitrate leaching potential in almond production systems. J Environ Qual 51:941–951. https://doi.org/10.1002/jeq2.20385

Jiang N, Hu B, Wang X, Meng Y, Chen B, Zhou Z (2019) Effects of crop residue incorporation and inorganic potassium fertilization on soil potassium supply power. Arch Agron Soil Sci 65:1223–1236. https://doi.org/10.1080/03650340.2018.1562174

Jones JB (2001) Laboratory guide for conducting soil tests and plant analysis. Extraction of Cl, NO_3, PO_4, K, and SO_4 from Plant Tissue, 1st edn. CRC Press, Boca Raton, pp 228–229. https://www.taylorfrancis.com/books/mono/10.1201/9781420025293/laboratory-guide-conducting-soil-tests-plant-analysis-jr-benton-jones

Kasongo RK, Verdoodt A, Kanyankagote P, Baert G, Ranst EV (2011) Coffee waste as an alternative fertilizer with soil improving properties for sandy soils in humid tropical environments. Soil Use Manag 27(1):94–102. https://doi.org/10.1111/j.1475-2743.2010.00315.x

Kassambara A (2023) ggpubr: ‘ggplot2’ Based Publication Ready Plots. R package version 0.6.0. https://cran.r-project.org/web/packages/ggpubr/index.html

Kaushal R, Verma K, Chaturvedi OP, Alam NM (2012) Leaf litter decomposition and nutrient dynamics in four multipurpose tree species. Range Manage Agrofor 33:20–27. https://www.researchgate.net/publication/258339972_Leaf_litter_decomposition_and_nutrient_dynamics_in_four_multipurpose_tree_species

Kone K, Akueson K, Norval G (2020) On the production of potassium carbonate from cocoa pod husks. Recycling 23. https://doi.org/10.3390/recycling5030023

Krishna MP, Mohan M (2017) Litter decomposition in forest ecosystems: A review. Energy Ecol Environ 2(4):236–249. https://doi.org/10.1007/s40974-017-0064-9

Kuznetsova A, Brockhoff PB, Christensen RHB, Jensen SP (2017) lmerTest package: tests in linear mixed effects models. J Stat Softw 82(12):1–26. https://doi.org/10.18637/jss.v082.i13

Li J, Lu J, Li X, Ren T, Cong R, Zhou L (2014) Dynamics of potassium release and adsorption on rice straw residue.

PLoS ONE 9(2):1–9. https://doi.org/10.1371/journal.pone.0090440

Lobel MR, Firth DJ, Johns GG (1994) Effect of mulch, Ca, and Mg on growth, yield, and decline of macadamia. Trop Agric 71(3):170–175. https://agris.fao.org/agrissearch/search.do?recordID=TT1998001102

Ludecke D, Ben-Shachar M, Patil I, Waggoner P, Makowski D (2021) performance: an R package for assessment, comparison and testing of statistical models. J Open Source Softw 6(60):3139. https://doi.org/10.21105/joss.03139

Martinez-Mena M, Carillo-Lopez E, Boix-Fayos C, Almagro M, Franco NG, Diaz-Pereira E, Montoya I, de Vente J (2020) Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. CATENA 187:104352. https://doi.org/10.1016/j.catena.2019.104352

Micke WC (1996) Almond Production Manual. University of California Division of Agriculture and Natural Resources. Publication 3364. https://anrcatalog.ucanr.edu/Details.aspx?itemNo=3364

Muhammad S, Sanden BL, Lampinen BD, Saa S, Siddiqui MI, Smart DR, Olivos A, Shackel KA, DeJong T, Brown PH (2015) Seasonal changes in nutrient content and concentrations in a mature deciduous tree species: studies in almond (*Prunus dulcis* (Mill.) D.A. Webb). Eur J Agron 65:52–68. https://doi.org/10.1016/j.eja.2015.01.004

Muhammad S, Sanden BL, Saa S, Lampinen BD, Smart DR, Shackel KA, DeJong TM, Brown PH (2018) Optimization of nitrogen and potassium nutrition to improve yield and yield parameters of irrigated almond (*Prunus dulcis*) (Mill.) D.A. webb. Sci Hortic 228:204–212. https://doi.org/10.1016/j.scienta.2017.10.024

Muhammad S, Sanden BL, Lampinen BD, Smart DR, Saa S, Shackel KA, Brown PH (2020) Nutrient storage in the perennial organs of deciduous trees and remobilization in Spring—a study in almond (Prunus dulcis) (Mill.) D.A. Webb. Front Plant Sci 11:658. https://doi.org/10.3389/fpls.2020.00658

Nagao MA, Hirae HH, Stephenson RA (1992) Macadamia: Cultivation and physiology. Crit Rev Plant Sci 10(5):441–470. https://doi.org/10.1080/07352689209382321

Nduka B, Adewale D, Akanbi O, Adejobi K (2015) Nursery soil amendments for cashew seedling production: a comparative analysis of coffee husk and NPK. J Agric Sci 7. https://doi.org/10.5539/jas.v7n3p111

Neilsen GH, Hogue EJ, Forge T, Neilsen D (2002) Surface application of mulches and biosolids affect orchard soil properties after 7 years. Can J Soil Sci 83(1):131–137. https://doi.org/10.4141/S02-034

Neilsen GH, Hogue EJ, Forge T, Neilsen D (2003) Mulches and Biosolids affect vigor, yield and leaf nutrition of Fertigated high density apple. HortScience 38(1):41–45. https://doi.org/10.21273/HORTSCI.38.1.41

Neilsen G, Forge T, Angers D, Neilsen D, Hogue E (2014) Suitable orchard floor management strategies in organic apple orchards that augment soil organic matter and maintain tree performance. Plant Soil 378(1):325–335. https://doi.org/10.1007/s11104-014-2034-8

Oyewole O, Omueti J, Rotimi R (2012) Growth of cocoa (*Theobroma cacao* L.) seedlings on old cocoa soils amended with organic and inorganic fertilizers. Afr J Agric Res 7(24):3604–3608. https://doi.org/10.5897/AJAR11.2045

Pinheiro J, Bates D, R Core Team (2023) nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-162. https://CRAN.R-project.org/package=nlme

Prescott CE, Vesterdal L (2021) Decomposition and transformations along the continuum from litter to soil organic matter in forest soils. For Ecol Manage 498:119522. https://doi.org/10.1016/j.foreco.2021.119522

Prgomet I, Gonçalves B, Domínguez-Perles R, Pascual-Seva N, Barros AIRNA (2017) Valorization challenges to almond residues: phytochemical composition and functional application. Molecules 22(10):1774. https://doi.org/10.3390/molecules22101774

R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. R version 4.1.2, RStudio 2022.07.1 build 554. URL https://www.R-project.org/

Reidel EJ, Brown PH, Duncan RA, Weinbaum SA (2001) Almond productivity as related to tissue potassium. Better Crops 85:21–23

Reidel EJ, Brown PH, Duncan RA, Heerema RJ, Weinbaum SA (2004) Sensitivity of yield determinants to potassium deficiency in 'Nonpareil' almond (*Prunus dulcis* (Mill.) D.A.Webb). J Hortic Sci Biotechnol 79(6):906–910

Rodríguez-Lizana A, Carbonell R, González P, Ordóñez-Fernández R (2010) N, P and K released by the field decomposition of residues of a pea-wheat-sunflower rotation. Nutr Cycl Agroecosyst 87:199–208. https://doi.org/10.1007/s10705-009-9328-x

Rosolem CA, Calonego JC, Foloni JSS (2005) Potassium leaching from millet straw as affected by rainfall and potassium rates. Commun Soil Sci Plant Anal 36(7–8):1063–1074. https://doi.org/10.1081/CSS-200050497

Soto RL, Martinez-Mena M, Padilla MC, de Vente J (2021) Restoring soil quality of woody agroecosystems in Mediterranean drylands through regenerative agriculture. Agr Ecosyst Environ 306:107191. https://doi.org/10.1016/j.agee.2020.107191

Sui N, Zhou Z, Yu C, Liu R, Yang C, Zhang F, Song G, Meng Y (2015) Yield and potassium use efficiency of cotton with wheat straw incorporation and potassium fertilization on soils with various conditions in the wheat-cotton rotation system. Field Crop Res 172:132–144. https://doi.org/10.1016/j.fcr.2014.11.011

Sumner DA, Buchner RP, Niederholzer F, Jarvis-Shean KS, Lightle DM, Symmes EJ, Milliron L, Stewart D (2019) Sample costs to establish an orchard and produce almonds Sacramento Valley. University of California Agriculture and Natural Resources Cooperative Extension. UC Davis Department of Agricultural and Resource Economics. https://coststudyfiles.ucdavis.edu/uploads/cs_public/67/b7/67b72c81-5ce0-4462-a396-fbb62ce8564e/2019sacvalleyalmonds.pdf

Tagliavini M, Tonon G, Scandellari, Quiñones A, Palmieri S, Menarbin G, Gioacchini P, Masia A (2007) Nutrient recycling during the decomposition of apple leaves (*Malus domestica*) and mowed grasses in an orchard. Agric Ecosyst Environ 118(1):191–200. https://doi.org/10.1016/j.agee.2006.05.018

Thomas GW (1982) Exchangeable cations. In: Page AL et al (ed) Methods of soil analysis: Part 2. Chemical and microbiological properties, 2nd edn. ASA Monograph Number 9, pp 159–165. https://acsess.onlinelibrary.wiley.com/doi/pdf/10.2134/agronmonogr9.2.2ed.frontmatter

U.S. EPA Method 200.7 (2021) Trace Elements in Water, Solids, and Biosolids by Inductively Coupled Plasma-Atomic Emission Spectrometry. https://www.epa.gov/sites/default/files/2015-08/documents/method_200-7_rev_5_2001.pdf

Wickham H, Chang W, Henry L, Pedersen TL, Takahashi K, Wilke C, Woo K, Yutani H, Dunnington D (2016) ggplot2: elegant graphics for data analysis. Springer-Verlag, New York

Wood SN (2011) Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. J R Stat Soc (B) 73(1):3–36. https://doi.org/10.1111/j.1467-9868.2010.00749.x

Xie K, Cakmak I, Wang S, Zhang F, Guo S (2021) Synergistic and antagonistic interactions between potassium and magnesium in higher plants. Crop Sci Soc China Crop J 9:249–256. https://doi.org/10.1016/j.cj.2020.10.005

Yang FK, He B, Zhang L, Zhang G, Gao Y (2020) An approach to improve soil quality: a case study of straw incorporation with a decomposer under full film-mulched ridge-furrow tillage on the semiarid loess plateau, China. J Soil Sci Plant Nutr 20:125–138. https://doi.org/10.1007/s42729-019-00106-y

Zeng Q, Brown PH, Holtz BA (2001) Potassium fertilization affects soil K, Leaf K concentration, and nut yield and quality of mature Pistachio trees. HortScience 36(1):85–89. https://doi.org/10.21273/HORTSCI.36.1.85

Zoca SM, Penn CJ, Rosolem CA, Alves AR, Neto LO, Martins MM (2014) Coffee processing residues as a soil potassium amendment. Int J Recycl Organic Waste Agric 3:155–165. https://doi.org/10.1007/s40093-014-0078-7