Characterization of almond processing residues from the Central Valley of California for thermal conversion

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ABSTRACT

Characterization of biomass relevant to thermochemical conversion processes and other applications is critical to the design and proper operation of energy conversion, biorefining, and other facilities, especially in regard to estimating critical problems related to fouling and slagging from ash constituents. Residue feedstock from almond production was obtained from seven huller and sheller facilities located throughout the Central Valley of California. Results of proximate (moisture, ash, volatile and fixed carbon content), ultimate (C, H, N, S, O composition), heating value, major and trace elements, and melting behavior analyses (all reported on a wt.% dry basis) reveal many similarities and also differences that potentially affect their utilization. The moisture content of air-dried feedstock is an average of 9.7% with only the separated hull material having a higher value (12.2%) and the fine component (<2 mm) a lower value (8.2%) on an as received basis. The volatile matter is relatively constant (72–76%). The ash content reflects a variable soil component in most fractions with a low average in shell of 3.5% and increasing to 22% in the fine fraction. The elemental C/O ratio is constant at about 1.15 and only appears slightly higher in the woody fraction (1.21). Nitrogen (0.4–0.8%) and sulfur (0.2–0.3%) are elevated compared to many other types of biomass, with the large variation in N probably related to irrigation water source and fertilization practices. Chlorine is generally low (<0.05) and varies without KCl control in both the crude feedstock and the ash. The ash of the almond biomass is very high in K, varying between 18–36% and only S, Ca, and P reaching substantial amounts. The trace element concentrations are mostly well below local soil compositions with only Ga, Sr, and Cu well above and thus suggest few, if any, regulatory utilization challenges. The elevated feedstock concentrations of S and N may be sufficient to cause some environmental concern for certain types of thermal conversion processes, mostly in relation to NO_x and SO_x emissions. The high ash content together with the very high K content can cause adverse bed behavior, corrosion, and fouling in boilers, despite the relatively high ash melting temperatures (>1100 °C) suggested by pellet fusibility test.

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1. Introduction

The Central Valley of California is the one of the world's most productive agricultural regions. Among the more than 400 commodity crops in the state, almond production is highly concentrated in the Central Valley and accounts for a major share of the total U.S. nut production, ranking second only behind dairy farms in value. With approximately 6000 growers, California produces 80% of the world's almonds and effectively all of the U.S. commercial supply. California's total edible almond meat production was just about 850,000 metric tonnes in 2012 of which about 580,000 tonnes went for export [1–3].

Almond processing produces large quantities of by-products of potential value for energy and other applications. Approximately 0.6 kg and 2.5 kg of shell and hull (dry basis), respectively, are produced

per kg of nut meat [1,4], which would generate 0.5 and 2.2 million dry metric tonnes per year of shells and hulls, respectively, based on current nut yield [5]. It has been estimated that 10–25% of the field weight brought to the process facilities is made-up of orchard debris, soil, and pebbles [4]. An additional 720,000 tonnes from tree pruning and orchard tree removals are not considered in the present study. The 2.7 million tonnes per year of clean shell and hull material represents 475 MW of electricity generation capacity if converted to energy [1,5].

Post-harvest almond processing facilities include hullers and shellers, where hulls and/or shells are separated from the almond meat, and finishing processing facilities, where the shelled meat is processed and packaged into finished product for distribution. Huller and sheller facilities are usually local within ~30 miles of the orchard, while the final processing facilities are regional and of a larger capacity.

The dairy industry uses almond hulls as feed and shells for bedding material. Dairies have reported paying more than $110 per metric tonne for hulls [6]. Shells are also sold to biomass power generation

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facilities as boiler fuel (~$33 per air dry metric tonne). Interest has been increasing in using these by-products at higher efficiencies or in more local cogeneration facilities both to support state level renewable portfolio standards and to reduce greenhouse gas emissions from fossil-based fuel combustion. The work described here was largely aimed at characterizing commercially available almond feedstock properties for use in thermochemical conversion, including gasification-based small (3–5 MWe) power generation and combined heat and power systems.

The Sacramento Valley, the northern half of the Great Central Valley of California (Fig. 1), receives about 500 mm of rain annually, but the San Joaquin Valley, the southern half of the Central Valley, is quite dry with substantially lower rainfall particularly on the semi-arid west side of the valley. Almond orchards are irrigated in both parts of the valley, but the San Joaquin production experiences lower water quality due to the greater use of ground water in supplementing imports of water from the north through the federal and state water projects [7]. As with other arid-land irrigation, salt management is a persistent problem for growers in the San Joaquin Valley and saline soils and soil solutions may influence the composition of the biomass [8]. The chemical composition of biomass feedstock is also influenced by a range of other factors including weather, crop variety, fertilization, harvesting procedures, and storage conditions. The extent to which all these factors influence chemical and physical properties of almond biomass is largely unknown, but is of critical importance to the design of regional energy conversion facilities. Where

produced on saline soils, high concentrations of alkali metals, chlorides, hydroxides, and other constituents potentially could lead to difficulties in thermal conversion due to ash transformations at elevated temperatures [9,10]. Ash slagging and fouling is a common occurrence when using high-silica, high-alkali feedstock in most combustion and gasification systems [11].

Chen et al. [12] provided a detailed review on the utilization of almond residues including gasification, pyrolysis, and combustion or co-firing (e.g. with coal). According to their review, there are few investigations of energy uses for waste from almond processing. Most are done for shell and tree pruning wastes. Especially in the case of pyrolysis, the shells were often first washed with water to remove dirt, which would have affected the ash composition and other properties [9]. González et al. [13] separately used almond residues (almond shell, almond tree pruning material, and almond hull) for gasification. Research appears to be lacking on thermal conversion of mixed and separated almond residues as generated by the processing facilities.

The objective of this research was to investigate the potential effects of different growing locations on the feedstock properties of almond processing by-products and to evaluate those properties most relevant to thermal conversion.

2. Methods

2.1. Feedstock selection and sampling

Representative samples were collected from seven huller/sheller facilities located throughout the Central Valley including both the Sacramento and San Joaquin Valleys (Fig. 1). These facilities process almonds [*Prunus dulcis* (Mill.) D.A. Webb] almost entirely from within the immediate surrounding region. All facilities processed the Nonpareil cultivar of almond that accounts for over 38% of the state total almond production. Details of the sample origins for all samples are given in Table 1. For reference, each feedstock is designated by number (prefixed by 'S') based on the location of their county or municipality of origin as shown in Table 1. The principal preparation and analytical methods used are summarized in Table 2.

Approximately 70 kg of almond shell mixtures (shell, hull, sticks, and a fines fraction in varying proportions) were gathered from large storage piles at each processing facility site. Shell mixtures were taken from the end of the pile nearest the plant discharge in order to obtain recently processed samples. One facility was not operating at the time of sampling and material was collected from the pile face near the point of the most recent discharge. The absence of lift equipment prevented the collection of material directly from the 12–15 m high auger discharge. Some variability occurs in the bulk density and particle size distribution of samples due to variations in the storage both laterally and longitudinally as a result of gravity separation as the pile builds from the overhead discharge (Fig. 2).

By products of the hulling-shelling process are typically collected in piles at different parts of the facilities. As noted earlier, residues are
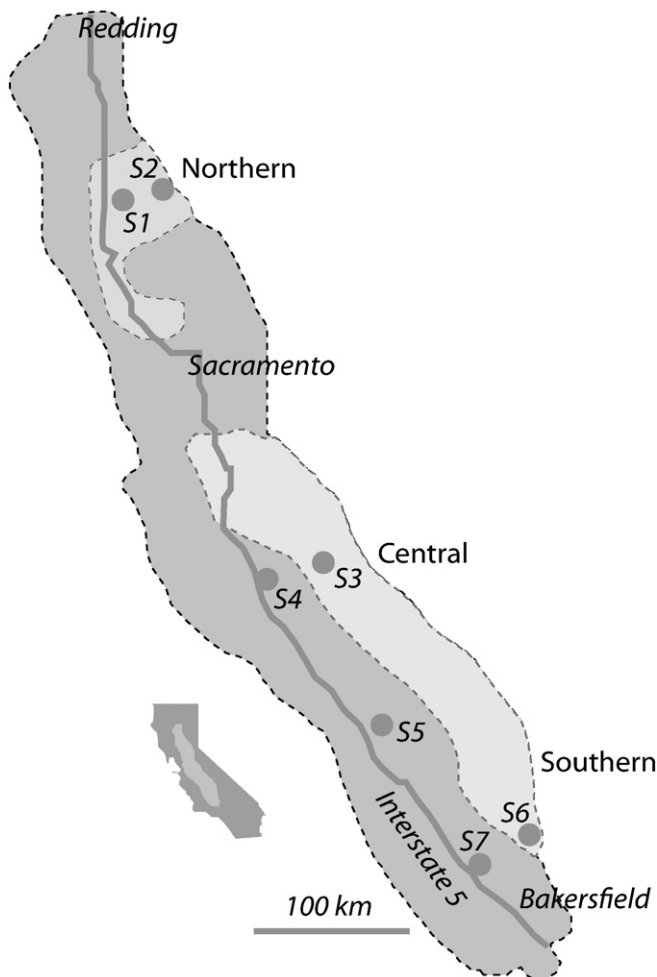

Fig. 1. Approximate sampling locations for almond huller/sheller residues from north to south in the Central Valley of California. The California Irrigation Management Information System [7] classifies the relatively high evaporation-transpiration zones 14, 15 and 16 on the western side (dark grey shade) of the Central Valley and the relatively low evaporation-transpiration zone 12 on the eastern side of the valley (light grey shade). Sampling sites S1 and S2 are in the Sacramento Valley, the remaining is in the San Joaquin Valley.

Table 1
Feedstock types and identifications.

County-City	Feedstock Information	Feedstock Code and Location
Glenn-Orland	Composite feedstock as received	S1 (north)
Butte-Chico	Composite feedstock as received	S2 (north
Merced-Ballico	Composite feedstock as received	S3C (central)
	Only shells 56.5%	S3S
	Only hulls 37.3%	S3H
	Only sticks (wood) 2.4%	S3W
	Only fine fraction 3.8%	S3F
Stanislaus-Newman	Composite feedstock as received	S4 (central)
Fresno-Coalinga	Composite feedstock as received	S5 (south)
Kern-McFarland	Composite feedstock as received	S6 (south)
Kern-Wasco	Composite feedstock as received	S7 (south)