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Research paper

Harvest storage and handling of round and square bales of giant reed and switchgrass: An economic and technical evaluation

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ABSTRACT

This study evaluated an innovative collection system for biomass based on single-pass harvesting to reduce handling and storage costs. Trials were conducted on two herbaceous perennials: giant reed (*Arundo donax* L.) and switchgrass (*Panicum virgatum* L.). A technical and economic evaluation compared two single-pass harvesting systems in which the biomass was cut-shredded-baled in the same operation. The two systems were composed of a Nobili biotriturator (for biomass shredding and windrowing) front-mounted on a 4-wheel-drive tractor and two types of balers: a KUHN VB2160 round baler and a KUHN LSB 1290 large square baler. Costs of harvesting, handling, storage and delivery to the conversion plant were evaluated. Three distances of delivering were considered (0–20; 20–40; 40–60 km). It was estimated that the harvesting system could produce round bales of switchgrass and giant reed stored in-field under a plastic tarp at a cost of 22.3 € Mg^{-1} and 23.3 € Mg^{-1} dry and square bales at 26.0 € Mg^{-1} and 21.7 € Mg^{-1} for switchgrass and giant reed respectively. The costs of harvesting, handling, in-field storage and delivery to the conversion plant amounted to 43.7 € Mg^{-1} and 45.7 € Mg^{-1} dry for round bales and 43.1 € Mg^{-1} dry and 34.9 € Mg^{-1} for square bales of switchgrass and giant reed for delivery distances of less than 20 km.

1. Introduction

Energy crops and agricultural crop residues have great potential as cellulosic biofuels and are fast becoming the most environmentally attractive and technologically feasible alternative to oil. While the technology and economics of handling, storing and delivering grain for the production of ethanol is well developed and understood, the commercial production of ethanol from cellulosic feedstocks has yet to become established [1] and techno-economic efficiency is required for producing biofuels from non-food feedstocks such as herbaceous energy crops. It is therefore important to determine optimal solutions for the field operations and logistics system for biomass collection and delivery to the biorefinery.

Several studies have confirmed that the key cost component in the logistics chain of herbaceous biomass from field to biorefinery is related to the field operations, in particular harvesting and biomass transportation [2] and the logistics system [3,1,4]. The low bulk density of biomass determines high storage and transport costs where volume is often the limiting factor rather than weight capacity of the means of transport. This problem can be reduced through in-field densification with round or rectangular balers or chopping with a self-propelled self-loading harvester for in-field handling [3,4].

Traditional harvest and handling systems and facilities designed for fodder crops are currently used for herbaceous biomass, so the challenge for the sustainability of the energy production chain is to define suitable and cost effective systems [4].

In our study a techno-economic analysis was conducted of the costs associated to the harvesting, storage and delivery of lignocellulosic biomass from two herbaceous energy crops: switchgrass (*Panicum virgatum* L.), a warm-season (C4) perennial grass, and giant reed (*Arundo donax* L.). Both crops are suitable for the climate and soil conditions in northeastern Italy and are considered as environmentally sustainable due to their very low soil tillage, pesticide and fertilizer requirements [5–8]. These crops can provide a suitable feedstock for biorefineries, also given that the Mossi & Ghisolfi Group (Biochemtex) has recently inaugurated a commercial-scale 50 million liters per year cellulosic ethanol production facility at

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Crescentino (northeastern Italy) that will use giant reed as feedstock, so a strong demand is anticipated for this crop.

While numerous authors have done significant research on switchgrass harvesting and logistics and associated cost analyses [9,2,1,10–12] there are few studies in the literature on giant reed.

Most of the studies on the harvesting and handling of herbaceous biomass describe systems with implements used for forage crops that involve two or three passes in the field (cutting, windrowing and baling) to obtain the baled product.

This study evaluates an innovative system that harvests in a single pass. The system is composed of a paired biotriturator and baler that chop and bale the biomass. Two baler models were evaluated, a round and a large square baler. The analysis derives from field observations on the performance that have determined the field and material capacity of the harvesting system and associated costs. The economic analysis is thus based on effective measurements of machinery field capacity. It is assumed that the individual farmers produce and store the crops on the basis of delivery contracts with the biorefinery.

In the analysis it was hypothesized that, as happens in Italy for fodder crops, each farm creates a storage area of feedstock bales near the fields that will later be sent to the conversion plant on the basis of agreed delivery plans. Because of the wet climate in northeastern Italy, all the bales must be collected rapidly after baling and stored under a roof or covered with a tarp to prevent rain wetting the bales and affecting the biomass quality.

The following were determined in the study: i) field performances of a single-pass system with round and square baler, ii) cost analysis of the two harvesting systems iii) cost evaluation of the in-field storage system with round and square bales and successive product delivery.

2. Materials and methods

Two herbaceous perennial crops were considered, giant reed (*A. donax* L.) and switchgrass (*P. virgatum* L.). The crops were grown in Ferrara province, northeastern Italy (Lat. 44°37′09″N, Long. 11°45′58″E; 4 m a.s.l.), were 8-years-old and the experimental fields covered 6500 m^2 for both crops.

Giant reed was in a plantation obtained with rhizomes of an ecotype selected at the University of Catania, 1 × 1 m planting layout. Switchgrass, variety Alamo, was sown in rows 0.45 m apart at a rate of 600 PLS (pure live seed) per square meter. Both crops were harvested in the first ten days of March 2012 before the onset of the vegetative period when the soil was sufficiently dry to support the weight of machines and the moisture content of the two crops was compatible with baled storage.

2.1. Harvesting systems

The two crops were harvested using a single-pass system that contemporarily cut, shredded and baled the biomass. The cutting and shredding was done with an RM 280 BIO biotriturator (Nobili S.p.A., Molinella, Italy) suitable for harvesting biomass crops such as giant reed, switchgrass and fiber sorghum (*Sorghum bicolor* L. Moench) [13]. It was front-mounted on a 4-wheel-drive tractor with a three point hitch. The baling was done with a KUHN VB2160 round baler and a KUHN LSB 1290 large square baler (KUHN S.A. Saverne, France) rear-mounted on the tractor (Fig. 1). The harvesting system with the round baler used a CNH T6090 tractor, while for the harvesting with the square baler a CNH T8.300 (CNH Industrial N.V. Essex, UK) was used to cope with the greater power absorbed by the baler. Both tractors had an Engine Power Management System that can deliver a power boost up to 148 kW for CNH T6090 and 202 kW for CNH T8.300.

The round baler was a variable chamber that wrapped the bales in nets while the square baler was high density and secured the bales with 6 knotted twines; these are the most common wrapping systems for fodder crops in the area.

The actual field area capacity, C_a [14], of the machines was evaluated on the basis of the working times measured during the field trials not considering times for refueling, adjustments or installing net and twine.

The round and square bales were measured and weighed in the field. The bulk density was determined on a wet basis. The moisture content was measured on samples of about 2 kg of biomass taken from the bales.

2.2. Logistics

A production chain was hypothesized that involves a catchment area of farms producing biomass that deliver bales to the biorefinery on the basis of need. Given that conversion plants require a steady flow of deliveries, in the analysis it was assumed that the bales were transported by a farm tractor equipped with a loader to a field storage area and stored for about three-six months before being shipped by truck to the biorefinery.

A handling and storage model of the biomass was simulated referring to the normal practices adopted by the agricultural contractors specialized in the baling of straw and hay and using bales of the same size. The times were measured directly in the field referring to the same operations done by contractors during hay making.

Even if for round bales the rounded top sheds water [15,2], to preserve the biomass quality and reduce dry matter losses [16,17] it was assumed that the stored round and square bales would be covered by a cheap plastic tarp (Fig. 2). This storage system is commonly used by farmers in the area for hay and straw bales to avoid indoor storage that determines a high incidence on the costs [9,18]. The bales are accumulated in a covered stack and can be stored for some months. All bales were placed on discharged pallets to avoid contact with the ground. The storage location was chosen close to a road to provide needed access for trucks and at a maximum distance of 400 m from the field. Deliveries begin in April (end of the harvesting period) and last at most until September. In this period, thanks to the generally favorable weather conditions, access for the trucks can be guaranteed. A 14 m by 30 m tarp was used to cover the stacks of both types of bales; 150 round bales (4 layers, 60 + 45+30 + 15) and 150 square bales (5 layers, 40 + 40+40 + 20 + 10) can be stored under this.

It was assumed that the bales will be handled using an Iron 40M loader fork (Sigma 4 Spa, Ravenna, Italy) front-mounted on a CNH T5070 kW 78. The loader handles two bales at a time for transport and formation of the stack in the storage location and in 10 h of work can carry 300 round bales or 350 square bales to the stack. In Italy, truck haulage is used for transporting bales from the field to the conversion plant. The truck-trailers usually have 30 Mg of legal weight capacity with a potential transport volume of 40 round bales or 44 large square bales. After the period of storage the bales are loaded on the truck by the loader fork with an average loading time (measured on hay bales of the same size) of 50 min for both bale types. To estimate delivery costs three distances from the storage site to the conversion plant were assumed: 0–20, 20–40 and 40–60 km as the contracts with the haulage companies depend on the distance covered. It was also assumed that the unloading will be done at the conversion plant at its expense.

2.3. Costs evaluation

The total machinery costs included charges for ownership and