Engineering Aspects of Production and Harvest Mechanization for Fresh and Processed Vegetables

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ADDITIONAL INDEX WORDS. harvesting

SUMMARY. Production and harvesting systems for processing vegetables have been highly mechanized, however, field efficiencies are generally low, and high field losses and fruit damage continue to limit profits for several crops. By comparison, the number of fresh market crops currently machine harvested is small, and research to develop new harvesting technology for these crops is limited. Current mechanization research includes improvements to existing production systems, development of harvesters for crops currently hand-harvested, and the integration of new technologies into current (and future) production systems. Mechanical harvester-based production systems are evolving that reduce field losses and fruit damage, improve recovery, and decrease the foreign materials in the harvested product. However, improved cultural production systems and crop varieties that are adapted for once-over machine harvest are needed. An integrated approach in which crop characteristics along with planting, cultivating, and harvesting techniques are considered will be necessary to develop profitable and highly efficient alternatives to hand-harvest production. The integration of new technologies including differential global positioning systems (DGPS), automatic machine guidance, and computer-based vision systems offers significant performance benefits, and is a substantial component of current vegetable production and harvesting research in the U.S. In time, as the

costs of these technologies decline, commercial adoption of these new methods is expected to increase.

In 2002, approximately 2.780 million ha (6.87 million acres) of vegetables were harvested with a farm value of \$14.8 billion (USDA, 2004). Fresh market production exceeded 0.781 million ha (1.93 million acres) with a value of \$9.28 billion, and vegetables for processing were grown on 0.546 million ha (1.35 million acres) with a value of \$1.33 billion. Other vegetable crops, including potatoes (*Solanum tuberosum*), dry beans (*Phaseolus vulgaris*), dry peas (*Pisum sativum*), lentils (*Lens culinaris*), and mushrooms (*Agaricus bisporus*), were produced on 1.453 million ha (3.59 million acres) with a total value of \$4.84 billion. It should be noted that many vegetable crops including sweet corn (*Zea mays* var. *saccharata*), potatoes, peas (*Pisum sativum*), green beans (*Phaseolus vulgaris*), tomatoes (*Lycopersicon esculentum*), and carrots (*Daucus carota* var. *sativa*) are grown for both processing and fresh markets. Over the last decade, the importance of vegetables to the U.S. population has grown as per capita consumption of these commodities increased 12% in the 1990s to 198.2 kg (437 lbs) in 2002.

Despite increased consumer demand for fresh and processed vegetables, a dwindling labor supply, growing concerns for government regulatory requirements, the consolidation of several large food processors and equipment suppliers, and increasing global competition have limited the growth and expansion of the U.S. vegetable industry. Additionally, methods for producing vegetable crops vary greatly depending on the crop and region. For some crops like sweet corn, advances in production methods and equipment can, in part, be attributed to research for grain crops. However, most vegetable crops require unique production techniques that necessitate the use of specialized equipment for mechanization.

The objective of this paper is to provide an overview of the status of mechanized vegetable production systems in the U.S., provide an overview of current mechanization research, and offers potential strategies for the development and improvement of

mechanized production systems for vegetables.

Status of mechanization for vegetables in the U.S.

In general, production systems for vegetable crops grown for processing have been highly mechanized. A detailed review of current equipment designs used in vegetable production was recently published (Glancey, 2003). Tillage, chemical application, and cultivation equipment are usually similar to those used for grain crop production. Planters for direct seeding or transplanting vegetables are generally designed for specific vegetable crops. Exceptions are sweet corn in which a conventional field corn planter with finger (plateless) or plate-type metering is used, peas in which a grain drill is used for seeding, and beans (snap, lima) in which bulk metering cups are used with a conventional row crop planter. Despite these examples, most direct seeded vegetable crops require precise seed metering and placement in the soil. Precision seeding is commonly used as a standard practice in most production systems. Although planters for precision seeding are expensive, the efficient use of seed, the improvement in uniformity and germination, and the elimination of subsequent population thinning operations usually make this planting method economically viable.

The relatively large areas of production with most processed crops justify the overhead costs associated with the relatively large and costly equipment required for mechanization. Fresh market producers, unlike most large vegetable processors, often cannot justify the costs of equipment, and must rely on hand labor for many production practices, especially harvesting.

Historically, harvest mechanization research and development has focused on processed vegetables. Currently, processed vegetable crops mechanically harvested include tomatoes, sweet corn, peas, potatoes, green beans, lima beans (*Phaseolus lunatus*), large pickling cucumbers (*Cucumis sativus*), peppers (*Capsicum annum*), spinach (*Spinach oleracea*), carrots, onions (*Allium cepa*), sugar beets (*Beta vulgaris*), and horseradish (*Raphanus sativus*). By comparison, the number of fresh market crops currently machine harvested is small and

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include green beans, potatoes, carrots and sweet corn.

Overview of mechanical production and harvesting systems for vegetables

Despite the wide variations in cultural practices and harvesting methods for vegetables, most production systems consist of four basic components. These primary components, illustrated in Figure 1, include a high yielding cultivar with a concentrated fruit set suitable for once-over harvest; cultural practices that promote high yields and uniform fruit as well as weed and disease free field conditions; a mechanical harvester that recovers and separates fruit; and several post harvest considerations including harvested product quality, stability, and processing characteristics. Together these attributes, their interactions, and the costs of production dictate the feasibility and performance of a mechanical harvesting-based system.

An important but often overlooked aspect of a harvest system is the interactions between these basic components. As suggested in Figure 1, each component interacts and affects the others, and these interactions can often dictate the success or failure of a production system. For example, cultivars with poor fruit setting architectures result in poor harvester recovery performance. Similarly, cultivars that produce fruit with thin skins that are susceptible to mechanical damage will impact harvester performance as well as post harvest processing and quality. Cultural practices clearly can affect the performance of a cultivar via weed competition or excess moisture that promotes diseases. In addition, practices that do not provide a level soil surface have been shown to affect

harvester recovery for several crops.

For crops with production systems that are not mechanized, future research and development must continue to recognize, understand, and improve these system components. System performance will ultimately be governed by the effectiveness of these constituents as well as their interactions and costs. Long term, an integrated approach that considers crop characteristics along with planting, cultivating, and harvesting techniques will be needed to develop profitable alternatives to hand-harvest production. This approach will also be critical for improving the performance of existing mechanized production systems.

Overview of current vegetable mechanization research

In the U.S., the reallocation of resources at land grant universities coupled with decreased research and development budgets at most equipment manufacturers has limited the amount of vegetable mechanization research in recent decades. However, contemporary mechanization research is ongoing with respect to several important issues, including: 1) improvements to existing mechanized systems; 2) the development of harvesters for crops currently hand-harvested; and 3) the integration of new technologies into current and future productions systems.

IMPROVING PERFORMANCE OF EXISTING HARVESTER SYSTEMS. Programs to improve harvester performance continue to focus on several issues including: improving harvester recovery, reducing mechanical damage, modifying cultural practices, and understanding the interaction between cultivar and harvester performance. This research is typically harvester and crop specific,

and is motivated by several factors. For lima beans and peas, in-field harvester losses frequently exceed 20% of yield (Glancey et al., 1996). Other machine harvested crops like processing cucumbers can average more than 10% damage in the harvested product. The resulting economic losses are high and may exceed \$200/ha (\$80.94/acre). Currently, research is focusing on alternate machine designs and cultural practices as well as improved cultivars that are more conducive to once-over mechanical harvest.

It is also important to recognize that traditional cultivar breeding and selection has focused on yield, disease resistance and postharvest characteristics. As a result, consideration of important cultivar attributes that affect mechanical harvesting has often been overlooked. These characteristics include fruit setting architecture and the ability to develop a uniform, concentrated set; stem strength; and resistance to mechanical damage. For some vegetable crops, especially those grown for fresh markets, poor cultivar performance with respect to these attributes currently prevents mechanized harvest.

DEVELOPMENT OF NEW HARVESTING SYSTEMS. Research to develop new harvesters for crops currently hand-harvested has been limited over the last 20 years. Several studies have examined cultivar performance in a once-over harvest production setting. Field trials with several squash (*Cucurbita maxima*, *C. moschata*) varieties found that yields from a once-over harvest were generally reduced by at least half compared to multi-pick hand-harvest yields (Glancey et al., 1998). Using a force balance shaker separation mechanism, field trials revealed that mechanical damage induced during fruit separation could be as high as 50%, which was unacceptable for fresh markets. In a similar study using only a simulated once-over destructive harvest, evaluation of densely planted okra (*Abelmoschus esculentus*) found that yields were lower than a multi-pick hand-harvest production system. A lack of concentrated fruit set was identified as the limiting factor (Wu et al., 2003a). Additional research with okra revealed that plant architecture as well as horticultural factors (N nutrition) did not affect the recovery of an experimental okra harvester, and that physiological factors appeared to

Fig. 1. An illustration of the four typical components in a mechanical harvester-based vegetable production system. In most instances, these system components interact and affect the performance of the others, and these interactions can often dictate the success or failure of a production system.

be limiting the feasibility of a densely planted, once-over mechanical harvesting system (Kahn et al., 2003; Wu et al., 2003b). However, research with other vegetable crops has suggested that plant architecture can affect harvester recovery. In processed lima bean production, recovery with a pod stripper combine was significantly higher with cultivars that set pods higher in the plant canopy. Conversely, cultivars that set more pods near the crown exhibited poor harvest recovery. Based on the harvesting characteristics of several different bean cultivars, a mechanical harvesting index for bush-type crops that relates the pod-setting architecture of a cultivar to harvest loss was developed (Glancey et al., 2004).

Research to develop new harvesters is ongoing for several specialty crops. A study in New Mexico examined cultivar and machine performance for mechanized fresh market and processed red chile peppers (Wall et al., 2003). Using a double helix separation mechanism, field trials found that harvester efficiency ranged from 73% to 83% across all cultivars; trash content of the harvested product varied from 25% to 42% of dry weight. In another study, paprika pepper varieties were harvested with both a conventional green bean harvester as well as a helix-type harvester; performance in each case was unacceptable. Subsequent work using a specialized harvester designed with a multi-brush separation mechanism, harvest loss across several Spanish varieties was reduced to 8% to 12% of the total crop production (Palau and Torregrosa, 1997). The advent and growth in popularity of fresh-cut, prepackaged vegetable products has led to an increased need for mechanization. Currently, several different baby leaf vegetables are being harvested with band-saw-type mechanical cutters that sever the crop close to the soil surface. For other crops like head lettuce (*Lactuca sativa* var. *capitata*), mechanical harvest aids are being used to assist hand-harvest operations. These devices not only improve productivity and reduce labor costs, but also increase food quality by minimizing human handling (Inman, 2003).

The limited research in recent decades to develop viable alternatives for hand-harvesting can be attributed to two basic reasons. First, crops that

are still hand-harvested in the U.S. are considered minor vegetable crops that have relatively small areas of production. This includes most fresh market production which tends to be owned and operated by small business enterprises. Owners typically cannot justify the expense of several machines to harvest multiple crops. Exceptions are sweet corn and green beans which can be machine harvested profitably by small operations with relatively simple machines. Second, the high research and development costs associated with the development of new harvesters cannot be justified given the limited economic return for such small markets.

INTEGRATION OF NEW TECHNOLOGIES INTO HARVESTING SYSTEMS. As computer microprocessors become more capable and affordable, the performance and corresponding cost of new, advanced technologies is becoming more feasible. For example, computer-guided robotic harvesting may offer several advantages over more convention harvesting methods. Although research over the last decade has focused primarily on fruit harvesting, prototype robots have been developed for asparagus (Arndt et al., 1994, 1997) and lettuce (Cho et al., 2002). These machines provide the opportunity for automatic and selective harvest which could significantly enhance the yield potential of several existing cultivars. As the relative complexity decreases and performance (specifically harvesting rate) improves, these systems will be become a viable alternative to both hand and once-over machine harvest.

A number of innovations have recently been introduced that have the potential to significantly improve several aspects of vegetable production. Using DGPS, spatial yield data have been collected using newly developed yield monitors that measure the mass flow rate of harvested product entering the harvester. This technology is being developed and tested for several vegetables, including tomatoes, potatoes, peas, beans, and pickling cucumbers. Other work has been initiated to understand the effects of spatial variations in soil properties and fertility on crop performance. Although the performance of the equipment necessary for site-specific production has generally been acceptable, the economic and environmental consequences of this ap-

proach in vegetable production are not well understood and need additional research (Roberson, 2000).

One of the most promising new technologies for vegetable production is guidance systems. Tractors and harvesters equipped with DGPS capable of real-time kinematic (RTK) positioning have been used for several vegetable field operations. Although the costs are relatively high for this equipment, the benefits, especially for vegetable production, are potentially significant. Precision steering not only reduces the variation in row spacing between adjacent planter passes, but it also provides exact position information of each row. As a result, post-planting operations can utilize this position information for machine guidance purposes. For example, once a crop has been planted with a precision guidance system, cultivation can be performed in close proximity to the crop without damaging roots; subsurface irrigation tubing location is known and can also be avoided. In addition, several subsequent field operations can be semi-automated and can be performed at a higher velocity as well as at night. Specific mechanical harvest production systems that utilize these technologies for vegetables are currently under development (Upadhyaya et al., 1999).

Machine vision systems are being examined for their potential to enhance performance of several vegetable machine operations including harvesting. Cameras are currently being used to identify crop rows as well as pests. In addition, research is ongoing in which cameras are being used to identify harvested and unharvested regions within a field for the purposes of automatically guiding vegetables harvesters. This work is utilizing multi-spectral images as a means to enhance the subtle differences in appearance of a crop frequently observed with conventional cameras using only visible light (Vassallo et al., 2002).

Conclusions

Production systems for vegetable crops grown for processing have been highly mechanized. However, profitable alternatives to hand-harvest production systems are still needed for several crops, especially fresh market vegetables. Factors limiting development include the high costs associated with new harvester development as

well as the limited potential market for specialty harvesters for these minor crops.

Clear interactions exist between the cultivar, cultural practices, a mechanical harvester and several postharvest requirements. As a result, a system-level approach is critical for developing economically viable, highly automated vegetable production systems. Furthermore, improvements in plant architectures and yields and other modifications to crops are required before some vegetables can be machine harvested. Some of the attributes requiring further development include, but are not limited to, better fruit location within the plant structure, more uniform fruit sets, increased mechanical damage resistance, prevention of premature or difficult fruit detachment, and more robust postharvest quality and stability.

The integration of new technologies including DGPS, automatic machine guidance, and computer-based vision systems offers significant performance benefits, and is a substantial component of current vegetable production and harvesting research in the U.S. As costs continue to decrease for these new technologies, commercial adoption will increase.

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Engineering and Horticultural Aspects of Robotic Fruit Harvesting: Opportunities and Constraints

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SUMMARY. Automated solutions for fresh market fruit and vegetable harvesting have been studied by numerous researchers around the world during the past several decades. However, very few developments have been adopted and put into practice. The reasons for this lack of success are due to technical, economic, horticultural, and producer acceptance issues. The solutions to agricultural robotic mechanization problems are multidisciplinary in nature. Although there have been significant technology advances during the past decade, many scientific challenges remain. Viable solutions will require engineers and horticultural scientists who understand crop-specific biological systems and production practices, as well as the machinery, robotics, and controls issues associated with the automated production systems. Focused multidisciplinary teams are needed to address the full range of commodity-specific technical issues involved. Although there will be common technology components, such as machine vision, robotic manipula-

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