FROM HAND HOLES TO VENT HOLES:
WHAT'S NEXT IN INNOVATIVE HORTICULTURAL PACKAGING?

Umezuruike Linus Opara

February 2011

From hand holes to vent holes: What's next in innovative horticultural packaging?

Inaugural lecture delivered on 2 February 2011

Prof Umezuruike Linus Opara
Department of Horticultural Science
Faculty of AgriSciences

Editor: US Taalsentrum
Design: Heloïse Davis
Printing: rsamprinters@gmail.com

ISBN: 978-0-7972-1286-2

ABOUT THE AUTHOR

Umezuruike Linus Opara was born on 1 July 1961 in a rural subsistence farming and hunting village, Umunam, in Imerienwe, Imo State, Nigeria, where he lived and obtained his primary and secondary education. He attended Upe/Umunam CMS (Anglican) Primary School, Upe Primary School and Umunam Central Primary School, receiving most of the first three years of classes in nearby rubber plantations, tree shades and other makeshift shelters during the Nigerian Civil War. At the end of his primary education in 1974, he baby-sat for one year before attending Owerri Grammar School, Imerienwe. He completed the West African Examination Council School Certificate examination in 1980 and won the annual Senior Essay Competition of the School for his essay entitled *1980 – The year of changes*, in which he prematurely and naively predicted a sudden end of apartheid in South Africa. After high school, he travelled to northern Nigeria and joined his parents in Yola, the capital city of present day Adamawa State in Nigeria, where he worked for two years at UTC (Nig.) Ltd, rising from the position of Sales Assistant to First Sales/Storekeeper. During this period, he used his weekends for self-study and in 1982 sat as an external candidate and passed both the General Certificate of Education examination and the Joint Admissions and Matriculation Board examination, and gained admission to study Agricultural Engineering at the University of Nigeria, Nsukka, in the same year.

Based on his first-year results, he was awarded the University of Nigeria Foundation Undergraduate Scholarship for Academic Merit in 1983, which he successfully retained throughout his undergraduate studies. He graduated with a bachelor's degree in Agricultural Engineering in 1987 with first-class honours (*cum laude*) and received the Department Prize for Best Graduating Student. He was an elected member of the University of Nigeria Students Union Senate (Upper House) and president of the National Association of Ngor-Okpala Local Government Students. In December 1987, he was awarded the prestigious Prize for Academic Excellence by the Mezie Owerri national community development organisation in Nigeria. For his National Youth Service Corps assignment, he spent one year as agricultural engineer at the National Centre for Agricultural Mechanization, Ilorin. He returned to the University of Nigeria in 1988 with a Federal Government Postgraduate Scholarship and completed his master's degree in Agricultural Engineering (*cum laude*) in record time in 1989. The results of his BEng honours thesis on *Nomograph models for selective agricultural mechanization* and his MEng thesis on *Computer-aided model for selective agricultural mechanization (CAM-SAM)* provided major inputs for the Agricultural Mechanization Study component of the 1989–2004 National Agricultural Development Strategy of Nigeria, of which he was co-leading author with the late Prof UGN Anazodo and Dr Taiwo Abimbola.

In 1988 he was awarded a New Zealand University Grant's Committee PhD Scholarship reserved for local students who made first class. He commenced his PhD studies in Agricultural Engineering at Massey University 1990 and completed in 1993. His dissertation on *Studies on stem-end splitting in apples* under the supervision of Prof Cliff Studman and Prof Nigel Banks provided the first scientific evidence linking the development of stem-end splitting with a precursor internal ring-cracking. Through the combination of engineering knowledge of the physico-chemical properties of fruit and horticultural science, industry guidelines were developed and disseminated on practical measures to predict and reduce the incidence of fruit-splitting damage. He subsequently held the position of postdoctoral researcher in the Department of Agricultural Engineering from 1993 to 1994.

He joined Lincoln Technology in Hamilton briefly as Postharvest Research Engineer but returned to Massey in 1995 as lecturer in Postharvest Engineering, was promoted to senior lecturer in 1999 and to program director for Engineering Technology in 2001, and was a founding member of the Centre for Postharvest and Refrigeration Research. He held several management and administrative positions, including that of coordinator of the Agricultural Engineering programme and coordinator of the BApplSc (General) programme. In 1993 he was awarded the inaugural Dean's Prize for Meritorious Contributions to the Affairs of the Faculty of Agricultural and Horticultural Sciences.

He was an elected member of the Massey University Governing Council (1993–1997), representing all internal and extramural students, and served on several council committees, panels and other university-wide committees, including the University Disciplinary Appeals Committee, chaired by the chancellor, and the panel for the appointment of a new vice-chancellor (1994–1995). He was also the residential community coordinator (1995–2001) responsible for mentoring and overseeing the welfare of students living in on-campus university accommodation. He was executive committee member of the Africa Association of New Zealand, president of the African Students Association, elected member of the Massey University Students' Association Executive, and president of International Students.

He is a chartered engineer (UK), currently chair of Section VI: Postharvest Technology and Process Engineering and executive committee member of the International Commission of Agricultural and Biosystems Engineering (CIGR), vice-chair of the Roots and Tuber section of the International Society for Horticultural Science, section chair for Engineering and Information Technology of the International Society for Food, Agriculture and Environment, and former vice-president (Postharvest Technology and Biotechnology) of the Asian Association for Agricultural Engineering (AAAE). He is a life member of the AAAE and the American Society of Agricultural and Biological Engineers, and member of several international and national scientific societies. At the 80th anniversary of the CIGR and the World Congress in Quebec in 2010, he received the CIGR Presidential Citation for significant contributions to the advancement of agricultural engineering in Africa.

He is founding editor-in-chief of the *International Journal of Postharvest Technology and Innovation* and member of the editorial board and regular reviewer for several international peer-reviewed journals. He has published over 60 articles in peer-reviewed journals and book chapters, co-edited three special issues of the *International Journal of Engineering Education* documenting recent advances in agricultural and biological engineering education, was the editor of two conference proceedings and made over 150 oral presentations at international conferences, including keynotes and invited lectures.

Prior to joining Stellenbosch University, he worked at Sultan Qaboos University in Oman (2002–2008), where he held the positions of associate professor of Agricultural Engineering, director of the Agricultural Experiment Station, assistant dean for Postgraduate Studies and Research, and acting dean during summer periods. During this period, he also developed a new research programme and courses in postharvest technology and received the university's Distinguished Researcher Award in 2006. He also served in many university and national policy and advisory committees, including the university's Academic Council (Senate), he was a member of the University Quality Audit Committee, which prepared the first quality audit report, and is a certified quality auditor of the Oman Accreditation Council.

He is active in the international development arena, serving as visiting expert on postharvest technology at the headquarters of the Food and Agriculture Organization (FAO) of the United Nations (UN) in Rome (2000–2001), agricultural mechanisation expert in Iraq for the FAO/UN (2001–2002), FAO expert panel on microbial safety of green leafy vegetables (2008), FAO expert on postharvest and marketing systems and member of the technical panel that developed an agricultural development strategy for Timor-Leste (2009) as well as a member of the International Advisory Board of the USAID Horticulture Collaborative Research Support Program (Hort CRSP).

Prof Opara holds the South African Research Chair in Postharvest Technology at Stellenbosch University, and his current research programmes focus on cold chain technologies, non-destructive technologies for quality measurement and mapping and reducing postharvest food losses.

He is married to Gina and has two daughters, Ijeoma (15) and Okaraonyemma (13), who both enjoy playing the piano and watching their dad play football.

DEDICATION

Far too many people to mention here have contributed immensely to my journey. I am gratefully indebted to them, and also thankful for the opportunities given to me. To my late parents, Pa Uzoma and Mama Okaraonyemma Opara, thank you very much for the warmth of your abiding love and sacrifices in providing the best for me and my brothers and sisters and the community at large. Papa, I will never forget your mantra: 'par excellence'. Thank you Papa for constantly reminding us that "onye shi anga aziamara ya adii mma jishienuike tugharia onwe ya" (the person who does not like the way he/she has been laid down by another person to sleep must learn to turn).

Mama, you have taught me to depend most on what I can do for myself and "emekwala omume uche" (not to give to be praised). I will always cherish those moments we shared in your kitchen and during the journeys on foot to Ihite, my maternal home, and to your other relatives. For allowing me to practice my English grammar by giving you evening lessons on how to speak and read English; for asking me to write my first letter on your behalf to Papa when I was in Primary 4 and subsequently recommending me to your friends for writing letters; for the brisk dawn walks to the farm, and the practical lessons about when, where, what and how to plant, weed, harvest and look after the produce; and for the long treks to the Nkworha, Ama Ulakwor, Ekisu and Orie Obibi markets to sell our agricultural produce, buy the goods we needed and save some of the income towards our school fees. These and much more have become important parts of my lifelong education. Mama Imela! (Thank you, Mama).

To my late brother, Opem Azunna Aloysius Opara (BA Hons, History/Archaeology, UNN), though you left us too soon, your light continues to shine through your exemplary foresight, wisdom and remarkable courage. Thank you for bringing home and spreading the good news about university education. In keeping that hope alive, this lecture is dedicated to you.

FROM HAND HOLES TO VENT HOLES: WHAT'S NEXT IN INNOVATIVE HORTICULTURAL PACKAGING?

ABSTRACT

The transition of the earliest human economy from hunter-gatherer activities to agriculture (including horticulture and fisheries) marked a major turning point in the evolution of modern-day societies, characterised by specialisation and the division of labour. As humans settled and nations emerged, the ensuing exchange and trade in agricultural products and services required technological development for handling, storage and transportation to local and distant markets. Packaging was central to the success of the new agriculture economy, allowing products to be handled in bulk; protecting them against inclement weather, physical damage and spoilage; and facilitating distribution and marketing. As agricultural trade expanded and competition grew, packaging further allowed competitors to differentiate and distinguish their products in the marketplace, thereby allowing them to offer premium-quality products to meet increasing market expectations. Horticultural food products are unique in that they remain alive long after harvest, 'breathing' in oxygen and releasing carbon dioxide, water vapour and heat. Given the critical importance of maintaining the cold chain in horticultural products handling, cost-effective packaging requires a delicate balance between ensuring the mechanical integrity of the package and maintaining low temperature and high relative humidity necessary to control the basic physiological processes that eventually lead to spoilage of produce. Vents provide a novel way of delivering chilled air and removing warm air around horticultural produce inside a container. To date, there are no industry standards or guidelines on the optimal vent size, number, area and location on the package. Understanding airflow patterns and the heat and mass transfer processes inside the package is critical for cost-effective package design. In this lecture, I will provide an overview of horticulture and packaging within the dynamic global food system, followed by a discussion of our research work on computational fluid dynamics (CFD) modelling to predict airflow patterns and heat transfer inside ventilated horticultural packaging as an example of the current challenges and opportunities in optimising packaging design. The grand challenges of the 21st century, including climate change, greenhouse gas emissions and rapidly declining global natural resources, have raised public concern about the contribution of packaging waste. Future prospects and challenges in achieving cost-effective and resource-efficient horticultural packaging will also be discussed.

Keywords: horticulture; cold chain; packaging; ventilation; CFD modelling; airflow pattern; heat transfer; sustainability

INTRODUCTION

Advancements in agricultural development has acted as both push and pull factors in shaping major milestones in human economic development. First was the transition from hunting-gathering to agriculture, which led to new and permanent forms of human settlement and the emergence of communities and modern societies. It is conceivable that horticulture preceded other forms of agriculture (field crops, livestock, fisheries, forestry, floriculture), given that the earliest humans were predominantly food gatherers who lacked postharvest skills and facilities to handle, preserve, process and cook food products from cereal grains and animals; thus relying mainly on 'ready-to-eat' wild food such as fruit, vegetables and nuts. With agriculture and the production of food beyond subsistence came the need to process, preserve, store, package, transport and trade/exchange, both on and off farms and out of season. More and better quality food brought better health, more reproduction, longer lifespan and more time for pleasure and luxury. Many would agree that the agricultural revolution spurred the Industrial Revolution, which began with the processing of agricultural raw materials such as cotton.

The significant rise in the human population due to better health and higher birth rates led to major concerns in the Malthusian era about the ability of agriculture to produce sufficient quantities of quality food to meet the needs of future population growth. At the same time, the Industrial Revolution created both the need and opportunities for more agricultural raw materials to meet the needs of an increasing proportion of people who continued to move away from the land (agriculture) into the burgeoning cities to engage in other specialised trade and service industries.

The success of modern industrial agriculture is underpinned by significant advances in postharvest technology, which enabled large quantities of food and other biomaterials to be handled, preserved, processed and traded across far distances around the globe (Opara, 2010; Rizvi, 2010; Opara, 2009a,b,c,d,e,f,g). Thus, kiwifruit produced in New Zealand, table grapes and Forelle pears grown in South Africa, bananas from Ecuador, pineapples from Ghana and yams cultivated in Nigeria can be bought from markets in other countries and continents all year round. Even where products are not subjected to postharvest treatment and processing, packaging is essential to move them from point of production to the consumer – *from farm to fork!* Like storage, packaging must be viewed as a *fundamental* postharvest technology that plays a critical role in modern agriculture and the global supply chain. In many ways, packaging is as an integral part of the food system. It also serves as a unit of measure and product differentiation. In the next section, I highlight the increasing importance of horticulture in the global food system.

A GLOBAL HORTICULTURAL REVOLUTION

A quiet but lucrative horticultural revolution has been going on in the global agri-food system. After many centuries of living in the shadows of food grains, there is now increasing realisation among policy and development practitioners of the significant contribution of horticulture in addressing human food security and nutrition needs. Global trade in fruit and vegetables (F&V) has shown a remarkable increase during the past 25 years; for the first time surpassing world trade in grains in annual monetary value in 1985 (Figure 1). This continuing rise in global trade also corresponds with rising production (Table 1) and consumption of F&V in many parts of the world, fuelled in part by increasing evidence linking F&V consumption to better health outcomes (Opara & Al-Ani, 2010a,b). Consequently, bananas and pomegranates grown in tropical and subtropical climates and apples and pears grown in temperate climates are available year-round in the international market. With the increased adoption of advanced technologies for water management and protected agriculture, a wide range of other types of F&V are also being successfully grown for both domestic and export markets.

A widespread perspective of food security among economists, development practitioners and some nutritionists is to characterise world food supply in terms of metric tonnes of cereal grain production or supply and relate this to demand (Nair, 2008; Rizvi, 2010). However, as recent changes in the composition of global agricultural trade have shown (Figure 1), I challenge the continuing validity of this approach in light of the emergence of horticultural crops (F&V) as the leading items of international food trade. Obviously, the dramatic rise in demand for and consumption of horticultural commodities during the past quarter century underscores their growing importance in our food system and food security as well. While cereal grains are well-known energy-dense food sources, it is equally important not to underestimate the role of F&V as important sources of micro- and phyto-nutrients, which have been demonstrated to contribute significantly towards reducing 'hidden hunger' (malnutrition) and the burden of non-communicable diseases such as diabetes, cardiovascular heart disease and cancer (Opara & Al-Ani, 2010a; Al-Ani, Opara, & Al-Rahbi, 2009). Furthermore, considering the multifaceted nature of food security (availability, access and utilisation), it is also important to broaden the debate to include the significant contributions of non-grain food industries such as horticulture towards improved food access at individual, household and community levels. Indeed, horticulture employs more people per unit of production than field crops, and recent studies in several countries (Weinberger & Lumpkin, 2007) have demonstrated that net farm income per family member was considerably higher in horticultural than non-horticultural smallholder farms, reaching close to 500% in Kenya (Table 2).

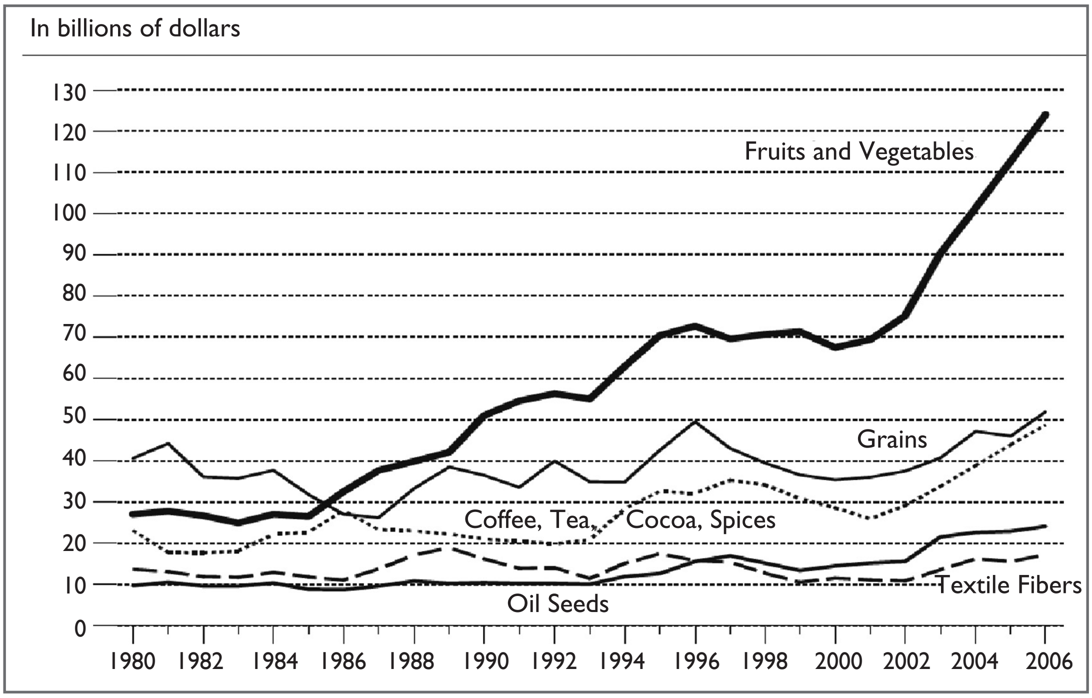

Figure 1: *World agricultural exports (FAOSTAT, 2011)*

	1979–1981*	**1989–1991**	**1999–2001**	**2003**	**2004**
Africa	61.9	82.2	107.5	115.3	117.4
Americas	126.9	156.5	198.3	202.5	206.9
Asia	249.1	380.7	696.2	818.8	841.1
Europe	135.9	135.2	144.9	139.7	148.4
CIS countries	47.1	46.2	39.3	47.3	47.6
Oceania	5.3	7.0	9.4	9.5	1.0
World	**629.7**	**812.7**	**1 207.6**	**1 345.1**	**1 383.6**

* *Average annual values.*

CIS = Commonwealth Independent State

Table 1: *Global production of fruit and vegetables (million tons) (FAOSTAT, 2011)*

	Difference in farm income (%)
Kenya	497
Lao PDR	380
Cambodia	117
South Vietnam	189
Bangladesh	29
North Vietnam	20

Table 2: *Net farm income per family member of horticultural versus non-horticultural smallholder farms (Weinberger & Lumpkin, 2007)*

WHAT IS PACKAGING?

The Encyclopaedia Britannica defines packaging as the technology and art of preparing a commodity for convenient transport, storage and sale. Strictly speaking, a package refers to a container and its contents, while packaging refers to the art and science of packing. However, in both science and industry, the words 'package' and 'packaging' are used interchangeably. Regulation EC no. 1148/2001 of the United Nations Working Group on Packages (http://www.unece.org/trade/agr/meetings/ge.01/2007/Packages_Germany.pdf) defines 'packages' as follows:

> Individually packaged part of a lot, including contents. The packaging is conceived so as to facilitate handling and transport of a number of sales units or of products loose or arranged, in order to prevent damage by physical handling and transport. Road, rail, ship and air containers are not considered as packages. In some cases, the package constitutes a sales package.

From a utility viewpoint, Coles (2003) offers the following perspectives on packaging:

- A means of ensuring safe delivery to the ultimate consumer in sound condition at optimum cost
- A coordinated system of preparing goods for transport, distribution, storage, retailing and end-use
- A techno-commercial function aimed at optimising the cost of delivery while maximising sales (and hence profits)
- A means of safely and cost-effectively delivering products to the consumer in accordance with the marketing strategy of the organisation

Coles (2003) further suggests that where brands compete, distinctive and innovative packaging is often the key to the competitive edge.

With respect to horticulture, the functions of packaging can be summarised in four categories:

[i] Containment – keeping and holding its contents secure between packing and consumption

[ii] Protection and preservation – against mechanical damage during handling, against deterioration by environmental conditions during distribution and storage and against contamination and deliberate abuse

[iv] Communication – identifies the content; legal requirements (e.g. labelling); promotion of sales; instructions for handling, storage and utilisation; display (e.g. retail display carton or tray); and branding

[v] Convenience and use – easy to open, close, dispense, dispose, recycle and reuse; information, eye appeal, warnings and distribution

Therefore, packaging plays a decisive role in the harvesting, handling, marketing, distribution and utilisation of horticultural products and other agricultural materials. For export-oriented countries like South Africa, it is fair to say that the success or failure of marketing depends to a large extent on the development and use of cost-effective and resource-efficient packaging: the type selected, its design features and how well it is suited to the contents, market expectations and supply chain logistics.

WHAT IS THE VALUE OF PACKAGING IN THE FOOD SYSTEM?

With increasing trade and demand for horticultural commodities comes the need for more product handling and sophisticated supply chain networks. In an era where international trade in agricultural commodities is facilitated by ever-improving transport facilities, precise and reliable marketing of packaged products becomes crucial to ensure timely delivery and the continuous availability of horticultural products. We realise that food production is only half the battle to feed an ever-increasing population. It does not end at harvest time; rather, there is a production-consumption continuum that includes a range of postharvest operations (Arnold, 1996). Farmers need effective connections to the next links in the postharvest chain, and packaging plays a crucial role in facilitating transportation, protecting fragile products such as F&V, regulating ripening, and simplifying storage, product identification, inventory control, invoicing and marketing.

As an example of the economic value of packaging, Table 3 shows the destination of food expenditures in the USA in 1995. While at the turn of the century US farmers received approximately 60% of the consumer's food dollar, they received less than 20% about 15 years ago (Austin, 1995), with packaging alone accounting for nearly 10% of the price of food. This data also shows the increasing importance of the postharvest sector in general, as nearly 78% of the US consumer's food dollar goes to postharvest activities. For relatively unprocessed foods such as fresh F&V, postharvest value added make up around 80% of the product's final value. Literature evidence showed that grading and packing accounted for over 21% of the contribution of postharvest operations to the unit cost of fruit in the UK apple market (Opara, 1995). With current trends in food purchase and consumption patterns towards demand for a wide range of products produced in distant locations and minimally processed ready-to-eat F&V, it is expected that the contributions of postharvest handling and packaging in particular to the price of food would be higher now and in the near future. Studies by Elitzak (1997) showed that packaging material costs in the USA food expenditures increased from 21 billion dollars in 1980 to 46.9 billion dollars in 1996. A recent analysis of the South African citrus value chain (Figure 2) showed that packaging alone accounted for more than 11% of product value during a specific week in the marketing period to Europe. The role of well-organised transport and marketing systems and the deployment of innovative storage and packaging technologies are therefore essential in capturing a large share of consumers' expenditures on F&V and other agri-food products.

Table 3: *What a dollar spent on food paid for in 1995 in the USA (Elitzak, 1995)*

Destination	Amount received (%)
Farm	22 .0
Labour	37.0
Packaging	9.0
Intercity transportation	4.5
Depreciation	3.5
Advertising	3.5
Fuel and electricity	3.5
Before-tax profits	4.0
Rent	3.5
Interest (net)	2.0
Repairs	1.5
Business taxes	3.5
Other costs#	2.5

Includes food eaten at home and away from home

DEVELOPMENTS IN HORTICULTURAL PACKAGING TECHNOLOGY

The types of packaging used in the horticultural industry have evolved in response to developments in materials science, market requirements and technological innovations in terms of our understanding of the physiology of plant and animal food materials. Although the origins of industrial packaging can be traced to leather, glass and clay containers, its economic significance has increased significantly since the start of the Industrial Revolution. From animal skin used in prehistoric times to the use of broad leaves of plants, calabash and clay pots to contain, transport and store agricultural materials, new horticultural packaging have been developed using wood, paperboard and plastic materials. Depending on the supply chain, market requirements and type of produce, packaging may be described as bulk (such as bins), layered (Figure 3), wholesale, retail, consumer or ready-to-eat packaging. Where additional protection is needed to maintain quality and control microbial contamination and decay such as in table grapes, multiple layers of packaging may be used.

The atmosphere around the produce inside a package may be normal air or modified, the latter commonly referred to as modified atmosphere packaging (MAP). MAP is an innovative hurdle technology that combines the benefits of cold storage (low temperature and high relative humidity) of horticultural crops with alterations in air composition (usually low oxygen and high carbon dioxide) to extend the storage life of the product (Caleb, Opara & Witthuhn, 2011; Yahia, 2009). Produce is enclosed inside sealed plastic film, which is slowly permeable to the products of respirator gases (O_2, CO_2, H_2O vapour), and changes in gas composition inside the package produce lower O_2 and higher CO_2 levels than in the fresh air (Figure 4). In MAP the barrier properties of the material are carefully selected according to the respiration characteristics of the fruit. The goal is to allow an exchange of gases and moisture that produces the optimal storage environment.

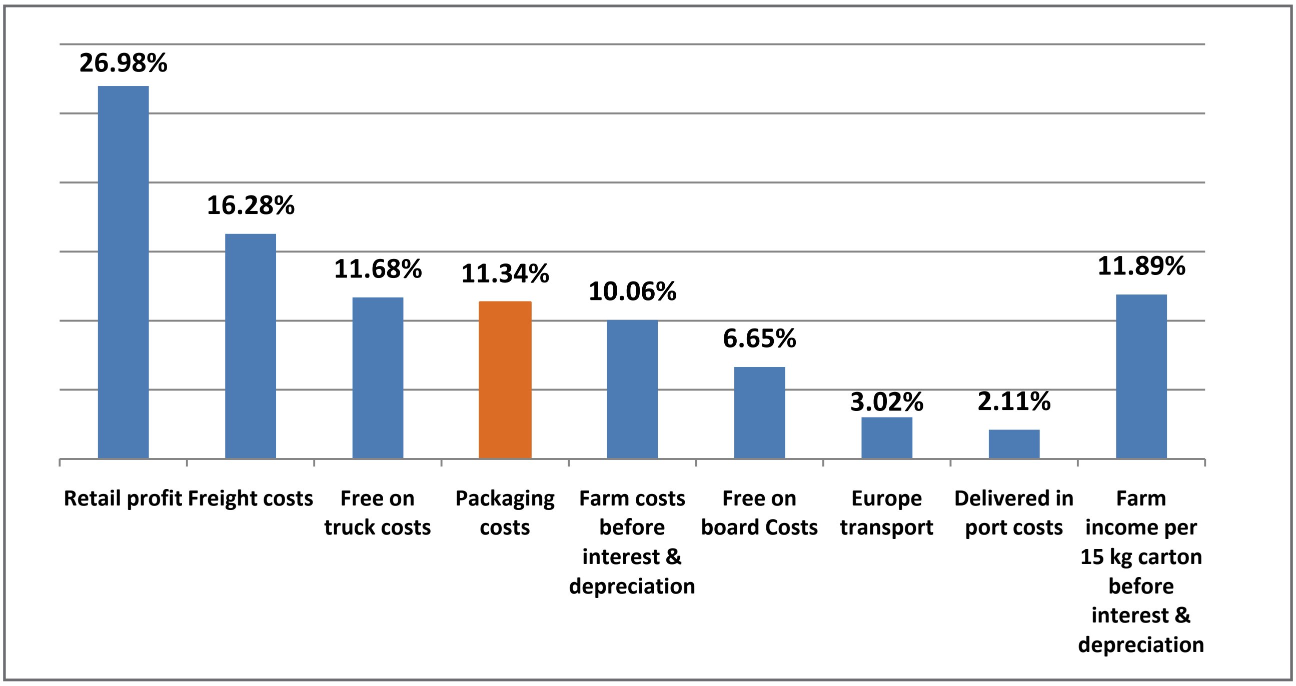

Figure 2: *Value chain costs and profits in a citrus supply chain (Siegruhn, 2010)*

Figure 3: *Standard apple carton with fruit placed on trays and packed in layers*

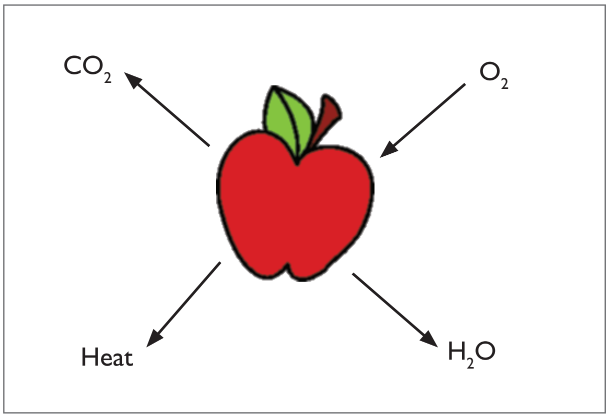

Figure 4: *The principle of respiration that underpins MAP*

With rapid advances in sensor technology as well as information and communication technology (ICT) to capture real-time information on environmental conditions, gas composition and physiological indicators of stress in produce, biosensors have been developed to monitor and control product quality inside a package. These developments have led to the emergence of the terms 'smart' and 'intelligent' packaging, which not only produces the optimal atmosphere for storage but also changes the barrier properties of packaging depending on the ambient temperature and physiological status of fruit. Smart packages offer properties that meet the special storage needs of specific products. For example, packages made with oxygen-absorbing materials remove oxygen from the inside of the package, thus protecting oxygen-sensitive products from oxidation. Temperature-sensitive films exhibit rapid change in gas permeability when they are subjected to temperature above or below a set point. These films change from a crystalline structure to an amorphous structure at a set temperature, causing the gas permeability to change considerably. Based on these developments, retails packages of produce such as kiwifruit and mango, which contain strips (sensors) that change colour corresponding to the degree of product ripeness, are now available in supermarkets.

TO VENT OR NOT TO VENT: THAT IS THE QUESTION

Horticultural commodities remain alive after harvest, consuming oxygen from the air around them and producing metabolic heat, water vapour and carbon dioxide. Given the deleterious effect of high temperatures on horticultural fresh produce, maintaining the cold chain is therefore critical in assuring the quality and safety of produce from orchard to table. To establish a cold chain and reduce the thermal stress in produce, air at low temperature and high relative humidity must be generated and delivered to the produce inside the package. This goal must also be balanced with the need to ensure the resistance of both the package and produce against mechanical stress due to impact, compression and vibration forces during handling. Excessive or insufficient venting will compromise the quality of both the package and the produce through their effects in maintaining the cold chain (Table 4) and energy cost of cooling. Singh, Mandal and Jain (2005) clearly demonstrated the benefits of packaging on fruit quality (Table 4) and also highlighted the need for proper design and the use of ventilation to balance the requirements of both produce and package (Table 5).

Table 4: *Effect of ventilation level in packaging material on fruit weight loss of peach under ambient conditions (Singh et al., 2005)*

Ventilation level (%)	**Weight loss (%) after days**				
	1	2	3	4	5
0	0.1	0.3	0.5	0.8	1.0
2.5	2.5	4.7	6.2	8.7	10.6
5.0	3.2	7.4	9.8	12.6	-
7.5	3.7	8.3	11.4	15.1	-
Control	5.7	16.8	24.6	34.6	-

Table 5: *Effect of ventilation level in packaging material on cumulative fruit rot of peach under ambient conditions (Singh et al., 2005)*

Ventilation level (%)	**Cumulative fruit rot (%)**				
	1	2	3	4	5
0	0.0	13.6	13.6	27.4	39.3
2.5	0.0	2.9	2.9	9.1	10.9
5.0	0.0	16.9	28.2	33.9	35.9
7.5	0.0	7.5	11.9	21.8	23.1

In addition to the metabolic heat generated by packaged produce, additional heat may also be transferred into the package via air leakage through doors and other openings and via conduction through the packaging material and storage envelope. Venting packages help to remove the excess heat inside and around the product, thereby reducing the rates of respiration, the degradation of produce and the incidence of postharvest loss.

Forced-air cooling (pressure cooling) is the most common method for precooling horticultural produce to the optimum storage temperature. Ventilated packaging is therefore required to achieve fast and uniform cooling. The cooling rate of produce depends mainly on heat transfer between cooling medium (air) and produce items inside the package. These heat transfer processes are closely related to airflow transport inside the package. The materials and configurations of packaging systems (trays, cartons, bins, palletisation and stacking patterns) have major impacts on the heat transfer and airflow patterns during forced-air cooling. Therefore, a packaging system needs to be carefully designed and evaluated before implementation to ensure cost-effective cooling.

In comparison to the long history of the horticulture industry that is characterised by constant innovation both in South Africa (Dodd, Cronjé, Taylor, Huysamer, Kruger, Lotze & Van der Merwe, 2008) and globally, the use of vented packages is fairly recent and was not standard practice and code requirements. About a quarter of century ago, a paperboard carton of apple fruit destined for either domestic or export market would likely have had two hand holes, one at each end of the package. By default, these hand holes performed dual functions: facilitating the handling and placement of the package in required positions along the supply chain, and letting air into the box to enhance the cooling of produce through convective heat transfer between the cold air and the warm produce. With increasing market demand for the reliable supply of quality-assured fresh produce with strict cold chain requirements, the need to quickly achieve the required product temperature and cooling rates became paramount. This posed considerable difficulties in packages without adequate ventilation and led to the emergence of a plethora of new ventilated package designs in the horticultural industry.

The performance of a ventilated package may be quantified in terms of airflow (rate, pattern/distribution), environmental control (temperature, relative humidity, and pressure), produce condition (cooling rate, mass loss, sensory quality) and cost-effectiveness (material, energy). Therefore, the design of packaging ventilation involves careful consideration of these factors to determine specifications of the vents in terms of size, number, shape, orientation, position on package and vent-to-package surface area ratio. Several authors have experimentally investigated the ventilation requirements of produce packaging to estimate the vent requirements. In a study on citrus, Ladaniya & Singh (2000) reported that ventilation by up to 6% of the side areas of the box provided better aeration during precooling in shipping containers. According to the authors, 4 to 5% of the side areas punched as four long slits (9.5 cm x 1.75 cm) and 1.65% of the end area punched as one slit (8 x 1.7 cm) as a handling slot were found sufficient. Similar studies on flower packaging ventilation (Nowak & Rudnicki, 1990) showed that packaging used during forced-air cooling must have vents on either end and that total vent size should equal 4 to 5% of the area of the end wall of the box. The authors concluded that wrapping must not impede airflow.

THINKING OUTSIDE THE BOX: QUANTIFYING FLOW INSIDE PACKAGING

It is usually expensive, time-consuming and situation-specific to only use experimental methods for studying heat transfer and airflow processes. Alternatively, mathematical modelling is overall a cost-effective strategy for predicting the airflow patterns and temperature variation in controlled environments such as ventilated packages. If information on the packaging system, cooling conditions and product properties is used as model input data, the results obtained can predict the effects of these factors on airflow patterns and cooling rate.

The geometry inside a bulk or layered packaging of horticulture produce such as fruit is very complex, comprising of the produce, air, package and voids (Figure 4). Until recently, research on refrigerated storage and handling of such packaged products focused on gaining better understanding of the cold store performance through data logging of the environmental conditions inside the cold store and product temperature. Modelling such complex structures was even more difficult, and this led to the application of heuristic and empirical models to quantify heat and mass transfer process outside and inside the package (Amos, 1995; Tanner, 1998; Tanner, Cleland & Opara, 2002; Tanner, Cleland, Opara & Robertson, 2002; Tanner, Cleland & Robertson, 2002).

In general, three types of models have been developed for predicting airflow patterns and heat transfer in horticultural packages or refrigerated spaces during cooling processes. The first type is the *zoned model* (Amos, 1995; Tanner, 1998), in which the domains considered were divided into a number of zones. Airflow was modelled by defining an airflow pathway according to experimental data. Energy and water vapour mass balances were performed on each zone to determine air temperature, air humidity ratio and the temperature of products and packaging materials. The zoned model requires much less computing effort, and it is easy to write computer codes for model solutions. However, since the airflow patterns were estimated from measured data for certain packages or coolstores, this approach limits the model application under different package designs or coolstore arrangements.

The second type is the *fully distributed model*, which applies numerical methods to solve two-dimensional or three-dimensional mass, momentum and energy conversation equations (Wang & Touber, 1990; Zou, 1998). As the airflow patterns are solved explicitly, no experimental data is required to run the model. If the model is used for the transport processes within a produce package, a complex body-fitted grid system has to be generated to describe the complicated geometries inside the package, which could be a daunting task for most model users. The difficulties in grid generation for detailing the geometries of different types of packaging systems largely reduced the accessibility of this type of model.

The third type is the *porous media model* (Tassou & Xiang, 1998; Xu & Burfoot, 1999), in which produce items inside the packages are treated as saturated porous media. Macroscopic volume-averaged transport equations are solved to find the volume-averaged velocity and temperature. Since certain information with respect to microscopic structure is lost in the spatial averaging process, a set of empirical parameters is required for the closure of the macroscopic equations. These parameters are found in the expressions for porosity, permeability, Forchheimer constant, thermal and mass dispersion, and interfacial heat and mass transfer coefficients. The volume-averaged approach eliminates the need to generate complicated meshes to describe the geometric details of the packaging systems. Therefore, the porous medium models usually require less computing capacity than the microscopic models. However, these studies (Tassou & Xiang, 1998; Xu & Burfoot, 1999) only dealt with some specific cooling conditions and bulk containers, and thus were not readily applicable to a wide range of packaging systems and horticultural crops.

To provide input data for the heat and mass transfer models of horticultural packaging, spot measurements were made outside the package using hotwire anemometers to quantify airflow outside the package, while in-package flows were estimated indirectly by Tanner, Cleland, Opara and Robertson (2001) using a CO_2 sensor to sample air in designated locations. While these studies provided good insights into the thermodynamics inside the coolstore and package of fruit, the zoning strategy adopted by Amos (1995) and the combination of intra- and inter-zonal transfer approach by Tanner (1998) lacked the spatial detail and accuracy to predict and visualise airflow patterns. Altogether, these approaches to understanding airflow and cooling performance of packaged produce provided useful but macro insights into thermodynamic processes inside ventilated packaging. Better understanding of the airflow patters at the micro scale inside the package was still required to partly explain some of the variations in product cooling rates and the incidence of physiological disorders and spoilage. The work of Amos, Cleland and Banks (1993) and Amos (1995) on modelling heat and mass transfer inside fruit coolstores, followed by that of Tanner, Cleland, Opara and Robertson (2002) on fruit packaging, laid the foundation for our subsequent research into airflow patterns and product cooling rates inside ventilated packaging.

ZOOMING INSIDE THE BOX: A POROUS MEDIA COMPUTATIONAL FLUID DYNAMICS MODELLING APPROACH

Based on the insights and experiences gained in the previous studies, I initiated a new study to quantify and *visualise* airflow patterns and heat transfer inside ventilated packaging using computational fluid dynamics (CFD) modelling. The aim of this research programme was to develop a CFD modelling system for simulating airflow and heat transfer processes, and therefore to predict airflow patterns and temperature profiles in ventilated packaging systems during cold chain handling of fresh produce. Such a modelling system can find practical applications in evaluating forced-air cooling operations and assessing the cooling performance of alternative packaging designs for a range of horticultural commodities. CFD employs numerical methods to solve the fundamental fluid transport equations that are derived from the laws of conservation of mass, momentum and energy. The increasing capacity and decreasing cost of modern computers have made the application of CFD modelling more efficient and popular. In the next section of this lecture, I outline the modelling framework adopted and highlight some of the research outputs.

In the CFD modelling system we developed for fluid transfer inside ventilated horticultural packaging, the airflow pattern was modelled separately and the outputs were coupled into the heat transfer model as input data (Zou, Opara & McKibbin, 2006a,b).

Ventilated packaging systems modelled

Based on the way products are packed in the containers, these ventilated packages can be divided into the following two main types, as shown in Figure 6:

- Bulk packages, in which produce items are held in a bin or carton without any other packaging materials
- Layered packages, in which produce items are placed on a stack of trays

During forced-air cooling, bulk bins and cartons are grouped into pallets or stacks in front of fans or plenum. For secure palletisation, cross-stacked patterns may be used, as shown in Figure 5. To investigate the performance of a packaging system in terms of produce-cooling efficiency, both the characteristics of individual package (configuration, dimensions, vents and packaging materials, etc.) and the structure of the stack should be considered. Therefore, this study took account of two domains of the packaging systems: individual package and stacks of packages.

Description of the forced-air cooling system

In most forced-air cooling systems, the fans are closely positioned in front of one side of the stack, so the airflow conditions inside the package stack are very similar, and can be approximately described as follows:

- On the stack side close to the fans, airflow leaves/enters the vents with an approximately constant flow rate.
- On the stack sides other than the one close to the fans, airflow pressure is approximately equal to the pressure of the surrounding environment.
- If airflow enters a vent, it has the temperature approximately equal to that of the air leaving the evaporator of the cooling system.

Due to the similar airflow conditions inside the package stacks in different forced-air cooling systems, this study focused on the transport processes taking place inside packaging systems, and therefore avoided dealing with minor details of various cooling systems.

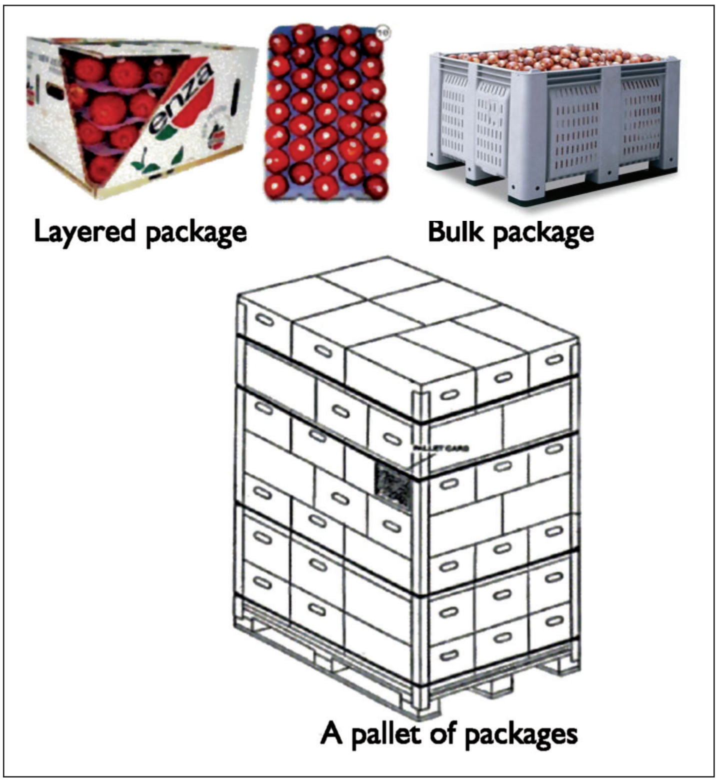

Figure 5: *Examples of layered and bulk packaging systems*

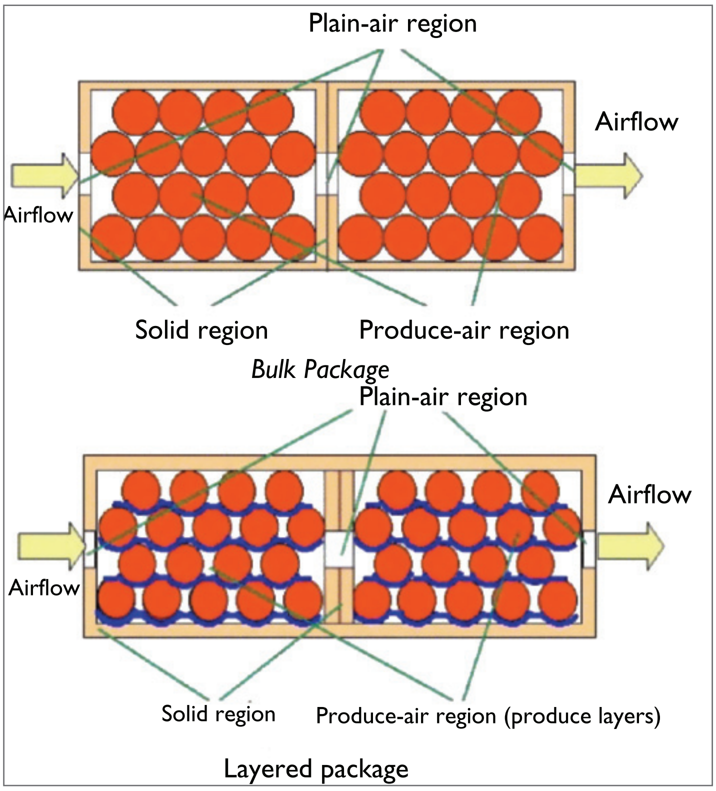

Figure 6: *Regions modelled in layered and bulk packages for fresh produce*

Modelling strategies

For both layered and bulk packaging systems, the domain inside an individual package or stack of packages can be divided into the following three types of regions, as shown in Figure 6:

- Produce-air regions (the void spaces and produce inside bulk packages and the void spaces and produce between trays in layered packages)
- Plain-air regions (the spaces in the vents)
- Solid regions (package walls and trays)

General analysis of transport processes

Since the air velocity is relatively large during forced-air cooling, the effect of buoyancy forces is considered negligible. By neglecting buoyancy forces, the heat transfer was assumed to have no effects on the airflow mass and momentum transfer. Therefore, airflow transport processes were treated as steady state, and the related airflow transport equations were decoupled from the unsteady-state heat transfer equations.

For airflow in a vent, the dominant direction for air movement and heat transfer is perpendicular to the package wall with the vent, so one-dimensional (1D) airflow and heat transfer in the vents were assumed. As produce items are packaged in boxes or bins, the individual produce item would likely receive minimal net radiative heat transfer (Tanner, 1998). Hence, it was assumed that the effects of radiative heat transfer were negligible. The range of air velocity (0.5–3.0 m/s) in forced-air cooling indicates that the possible changes in air temperature, pressure and moisture content will not cause any significant changes in most air properties. Thus it was assumed that air density, specific heat capacity, thermal conductivity and viscosity are constant.

Porous media treatment of produce-air region in bulk packages

To avoid dealing with the geometric details inside the packages, the porous media approach was adopted. Most fresh products are more or less sphere-shaped and have relatively uniform sizes. The dimensions of bulk bins are generally at least one order larger than the sizes of individual products. Therefore it was assumed that the produce-air regions inside bulk packages are isotropic, rigid, saturated porous media with uniform spherical particles.

Pseudo-porous media treatment of produce-air region in layered packages

The geometry inside a layered package is more complex than that of a bulk package. In general, the produce-air region inside the layered package is divided into several produce layers by the trays, as shown in Figure 7. The distances between two neighbouring trays usually have the same order as the sizes of produce items, so the strict porous media approach cannot be used. A pseudo-porous media treatment was employed to deal with the geometries of layered packages.

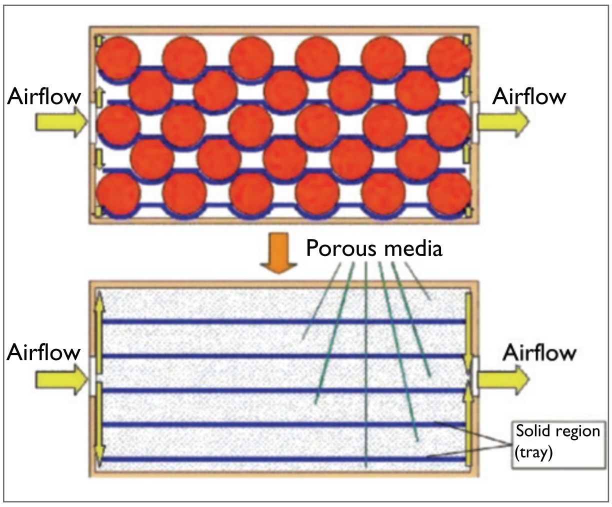

Figure 7: *Graphic illustration of the porous media for a layered package*

Airflow modelling

Airflow models were developed for both bulk and layered packages. The mathematical model for airflow in bulk packaging systems consisted of the following equations:

- Continuity equation for air mass conservation in the plain-air regions
- Volume-averaged continuity equation for air mass conservation in the produce-air regions
- Equations for describing air momentum conservation in the plain-air regions
- Volume-averaged momentum equations for air momentum conservation in the produce-air regions
- Auxiliary algebraic equations for the porosity and permeability in the produce-air regions

Similarly, the mathematical model for airflow in the layered packaging systems consisted of the following equations:

- Continuity equation for air mass conservation in the plain-air regions
- Volume-averaged continuity equation for air mass conservation in the produce-air regions between trays
- Continuity equation for air mass conservation in the vertical tunnels (airflow between produce layers)
- Momentum equations for air momentum conservation in the plain-air regions
- Volume-averaged momentum equations for air momentum conservation in the produce-air regions between trays
- Momentum equations for air momentum conservation in the vertical tunnels (airflow between produce layers)
- Auxiliary algebraic equations for calculating porosity and permeability in the produce-air regions

The air mass conservation in vents or in the plain-air regions is described by the 1D continuity equation (Bird, Steward & Lightfoot, 1960):

$$\frac{\mathrm{d}u}{\mathrm{d}x} = 0$$
$$\frac{\mathrm{d}v}{\mathrm{d}y} = 0$$

where u is the air velocity component in the direction of the x-axis, m s^{-1}; and v is the air velocity component in the direction of the y-axis, m s^{-1}.

The air mass conservation in the produce-air regions is described by the volume-averaged continuity equation (Zou et al., 2006a):

$$\frac{\partial}{\partial x}\left(\phi\langle u\rangle_{\mathrm{a}}\right) + \frac{\partial}{\partial y}\left(\phi\langle v\rangle_{\mathrm{a}}\right) + \frac{\partial}{\partial z}\left(\phi\langle w\rangle_{\mathrm{a}}\right) = 0$$

where ϕ is porosity; $\langle u\rangle$a is the intrinsic phase average of the air velocity component in the direction of the x-axis, m s^{-1}; $\langle v\rangle$a is the intrinsic phase average of the air velocity component in the direction of the y-axis, m s^{-1}; and $\langle w\rangle$a is the intrinsic phase average of the air velocity component in the direction of the z-axis, m s^{-1}.

The air-momentum conservation in vents is described by 1D Navier-Stokes equations (Bird et al., 1960):

$$\rho_{\mathrm{a}} u \frac{\mathrm{d}u}{\mathrm{d}x} - \frac{\mathrm{d}}{\mathrm{d}x}\left(\mu \frac{\mathrm{d}u}{\mathrm{d}x}\right) = -\frac{\mathrm{d}p}{\mathrm{d}x}$$

$$\rho_{\mathrm{a}} v \frac{\mathrm{d}v}{\mathrm{d}y} - \frac{\mathrm{d}}{\mathrm{d}y}\left(\mu \frac{\mathrm{d}v}{\mathrm{d}y}\right) = -\frac{\mathrm{d}p}{\mathrm{d}y}$$

where p is air pressure, N m^{-2}; μ is the air dynamic viscosity, N s m^{-2}; and ¯a is the air density, kg m^{-3}.

Details of all the mathematical equations describing airflow and the underlying assumptions in both bulk and layered packaging have been reported in Zou et al. (2006a).

Heat transfer modelling

Heat transfer models were also developed for both bulk and layered packages. The mathematical model for heat transfer in the bulk packaging systems consisted of the following:

- Air energy conservation equation in vents
- Energy conservation equation in the solid regions
- Volume-averaged air energy equation in the produce-air regions
- Volume-averaged product energy equation in the produce-air regions
- Energy conservation equation in single-produce items
- Auxiliary algebraic equations

Similarly, the mathematical model for heat transfer in the layered packaging systems consisted of the following equations:

- Air energy equation in vents or gaps between tray edges and package walls
- Solid energy conservation equation in package walls and trays
- Volume-averaged air energy equation in the produce-air regions
- Solid energy conservation equation in single-produce items
- Auxiliary algebraic equations

Air was treated as an incompressible fluid, and the 1D air energy equations were written as follows (Bird et al., 1960):

$$\frac{\partial(\rho_a C_a T_a)}{\partial t} + \frac{\partial(\rho_a u C_a T_a)}{\partial x} - \frac{\partial}{\partial x}\left(K_a \frac{\partial T_a}{\partial x}\right) = 0$$

$$\frac{\partial(\rho_a C_a T_a)}{\partial t} + \frac{\partial(\rho_a v C_a T_a)}{\partial y} - \frac{\partial}{\partial y}\left(K_a \frac{\partial T_a}{\partial y}\right) = 0$$

where t is time, s; Ca is the air-specific heat at constant pressure, J kg^{-1} K^{-1}; Ta is the air temperature, K; and Ka is the air thermal conductivity, W m^{-1} K^{-1}.

The energy equation for package walls was written as follows (Bird et al., 1960):

$$\frac{\partial(\rho_{\text{pack}} C_{\text{pack}} T_{\text{pack}})}{\partial t} - \frac{\partial}{\partial x}\left(K_{\text{pack}} \frac{\partial T_{\text{pack}}}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_{\text{pack}} \frac{\partial T_{\text{pack}}}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_{\text{pack}} \frac{\partial T_{\text{pack}}}{\partial z}\right) = 0$$

where ρpack is packaging material density, kg m^{-3}; Cpack is packaging material specific heat capacity, J kg^{-1} K^{-1}; Tpack is the packaging material temperature, K; and Kpack is the packaging material thermal conductivity, W K^{-1} m^{-1}.

Details of all the mathematical equations describing heat transfer and the underlying assumptions in both bulk and layered packaging have been presented in Zou et al. (2006a).

In summary, airflow and heat transfer models in bulk and layered packaging systems have been developed based on a porous media approach. The areas inside the packaging systems were categorised as solid, plain-air and produce-air regions. The produce-air regions inside the bulk packages or between trays in the layered packages were treated as porous media, in which volume-averaged transport equations were employed. This approach avoids dealing with the situation-specific and complex geometries inside the packaging systems, and therefore facilitates the development of a general modelling system suitable for a wide range of packaging designs, produce types and stacking arrangement inside coolstores.

Model solution and software development

The differential equations were discretised and the solution of the systems of discretisation equations followed the SIMPLER procedure. The GMRES (Generalised Minimum Residual) iterative method was employed to solve the systems of algebraic equations in each inner iteration step. Figure 8 shows the overall model-development strategy. The solvers were written in C language and Java interface was employed to integrate the solvers with the other model components. Software was developed to run the model (Opara & Zou, 2007; Zou et al., 2006b). Users interact with the software via three components: System Designer, Solution Monitor and Visualization Tool.

The modelling system developed and results obtained allowed airflow patterns and heat maps inside ventilated packages to be visualised (Figure 9). An experimental low-speed wind tunnel was designed and constructed with a see-through package section to study airflow inside a standard (18 kg) apple export carton. A comparison of the CFD model predictions with experimental observations of airflow pattern gave good agreement. Comparisons of model predictions of product temperature with data from fruit undergoing precooling in a coolstore also gave good agreement (Figure 10).

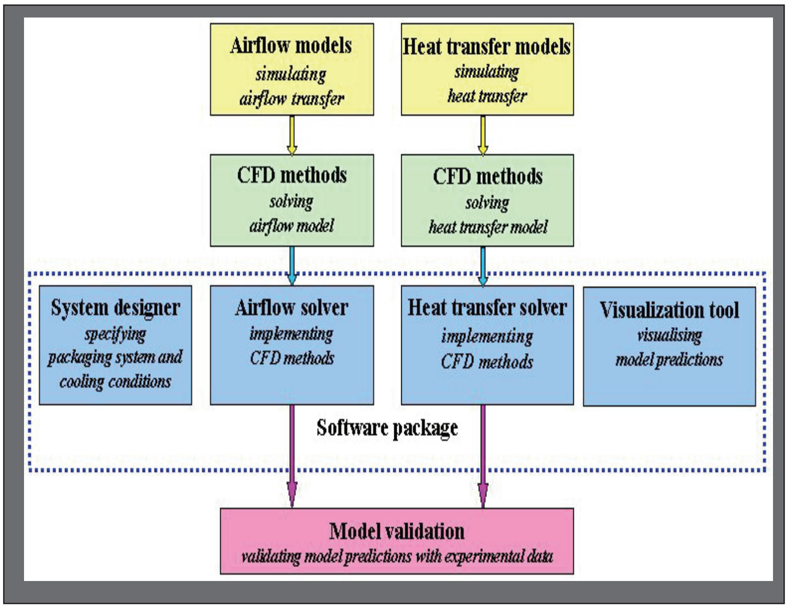

Figure 8: *Overall CFD modelling strategy*

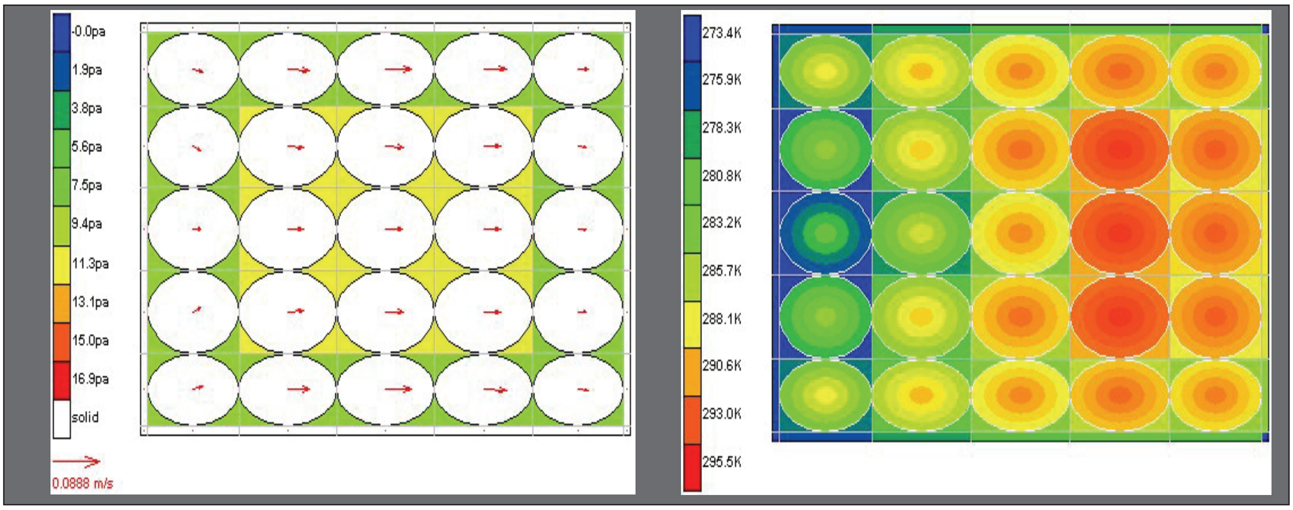

Figure 9 (top): *Visualisation of airflow patterns and temperature profiles*

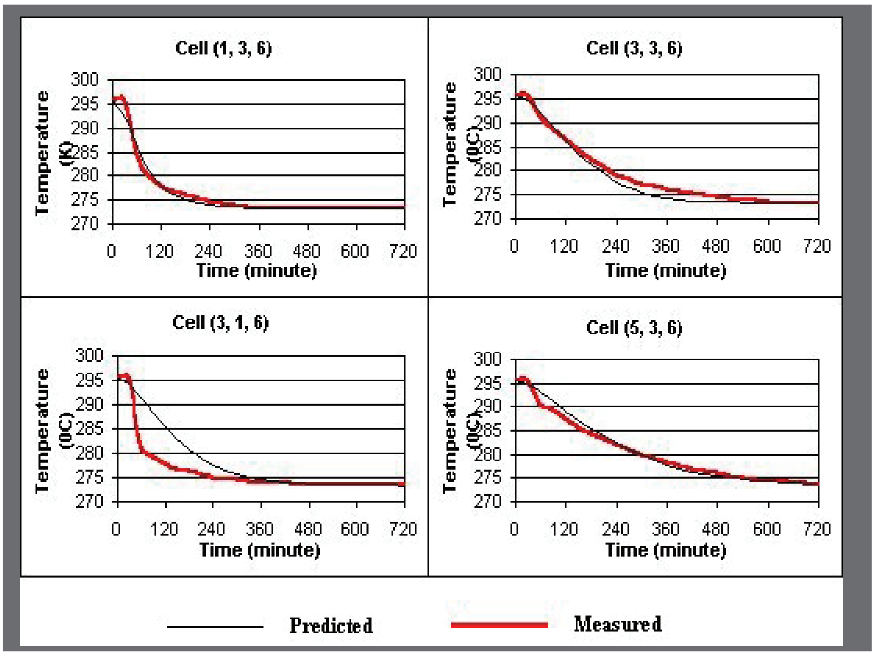

Figure 10 (left): *Comparison of CFD model predictions and measured experimental results*

WHAT'S NEXT: CRYSTAL BALL GAZING ON HORTICULTURAL PACKAGING

The first thing that I see is a bright future for horticulture and packaging, and this future lies in the ability of these industries and products to continue contributing to the food security, livelihood, health and welfare of an ever-growing human population. With the current global population of over 6.3 billion projected to reach 9 billion by 2050, and approximately 1.2 billion people – mostly in developing and transitional countries – presently undernourished or hungry, the availability and access to sufficient quantities of a wide range of quality, safe and nutritious food products remains one of the grand challenges of our time. Combined with climate change, rapidly diminishing natural resources and environmental degradation due to human activities, achieving sustainable food security becomes even more complex and dire. Horticulture and packaging are and must be at the forefront of the solution mix from the viewpoint of producing more food but also getting the products (inside packaging) to the market. Furthermore, there is overwhelming evidence from both epidemiological studies and clinical trials linking higher F&V consumption and better human health outcomes (Opara & Al-Ani, 2010a). So, in the medium to long term, increasing global trade in horticultural food products, which surpassed other agricultural products for the first time in 1985, will likely continue. It is also expected that future growth will be driven largely by exports of tropical, subtropical and novel horticultural crops, increasing consumer awareness about these products and the increasing global mobility of people. The success of this growth is invariably linked to the availability and use of packaging that satisfies the seemingly conflicting demands of the people, the environment and the product.

I also see formidable challenges for the horticultural industry that will impact on future packaging, and some 'in-house' challenges facing the packaging industry as well. Overproduction of some crops due to improved orchard management and extensive new plantings in emerging countries such as China and Chile, rising stiff competition in the global fresh produce market, restrictive phytosanitary and other regulatory measures imposed by importing countries and trading blocs, the colossal power of supermarkets and other global chain operators and the growing influence of the 'green' consumer are some of the factors exerting a huge influence on the future of horticulture. They equally impact indirectly on current and future horticultural packaging. There is also the persistent debate about who owns packaging and who decides on the design of the packaging of the future, raising questions about the influence of the various role players, from orchardists to packaging manufacturers to transporters and fresh produce importers.

Despite these challenges, packaging has long become an integral part of our everyday life and society at large. From gifts to food items and raw materials for other industries, packaging is necessary to contain, handle, protect and present products. However, like the wider agriculture industry and society it serves, packaging may have become a victim of its own success. So how should the packaging and horticulture industries respond to these challenges? How should packaging fulfil its vitally important roles to the horticultural industry and society at large? What should horticultural packaging look like in the year 2020?

The packaging of the future should be proactive in responding to the grand challenges of time: climate change, food security and resource and environmental sustainability. The packaging of the future must be cost-effective, resource-efficient and environmentally responsible. In achieving these, packaging must remain a viable business proposition – creating opportunities for employment and income, and facilitating more demand and consumption of horticultural products.

- *Sustainable packaging* – The concept of sustainable packaging requires that the production and utilisation of current packaging should not jeopardise the ability of future generations to access and enjoy the same products and services. This means that while maintaining its technical specifications for cold chain handling (low temperature, high relative humidity, mechanical strength), horticultural packaging should meet other equally important criteria: minimum raw materials required, biodegradable, reusable, recyclable, low resource input (energy, water) and limited carbon and water footprints. Hence, the 2020 packaging will likely carry a machine-readable label showing its total *sustainability index* based on a combination of attributes contributing to its resource content and potential environmental impacts and traceability.

- *Food safety* – One of the main functions of packaging is to protect its contents from contamination and spoilage organisms that might be harmful to consumers. However, there is also consumer concern about the potential impacts of packaging and manufacturing materials on the safety status of their contents and the consumer. An example is the potential migration of hazardous chemicals from a package to its contents, especially where adhesives and other chemicals are used. The glue and other chemicals used in the packaging of the future will be formulated from edible plant or animal materials.

- *Smart, intelligent packaging* – Major technological innovations, from refrigerated air storage to ventilated packaging and MAP, have dramatically changed the way we package and handle horticultural products. With ongoing rapid developments in what I call the technological innovation triad – biotechnology, nanotechnology and ICT (Opara, 2004), the living product (such as fruit) contained in packaging of the future will become the 'speaking produce' that is capable of sensing stress signals and communicating its physiological status to trigger real-time appropriate postharvest technological intervention and control. Smart nano- and femto-sensors embedded in smart and intelligent package materials will capture, analyse and transmit environmental stress signals communicated by 'speaking fruit', thereby triggering a series of controllers that adjust a range of stress response treatments (hurdle technologies) to maintain storage life, quality and safety.

- *Multiple packaging* – When we began our research on modelling ventilated packaging, we were driven by the curiosity to develop better understanding of the fluid dynamics and cooling rate inside the complex geometry of packages during the cooling of fruit. These fruit are commonly packed in bulk or layered packages (Figure 6). While modest progress has been made through our work and that of many other researchers using CFD modelling, the next immediate frontier lies in developing better understanding and optimising multiple packaging used for products such as fresh table grapes. Due to the specific cold chain and phytosanitary requirements to maintain product quality, the packaging system is comprised of an outer box in which a perforated polyliner is placed, followed by pouches (carry bags) that contain individual grape bunches, with an SO_2 absorber placed on top of the bags (to control decay), before covering with the liner and closing the box top (Ngcobo, Opara & Thiart, 2011). It is expected that the results of this CFD-based study will provide new insights into the perennial problems of stem and berry dehydration and decay commonly observed inside multi-packaging.

- *Packaging (and food) waste* – With increasing concerns among the general public and policy makers about climate change, environmental sustainability and food security, there is considerable interest in the environmental impacts of packaging and the role of packaging in food waste. Surely, packaging has a crucial role to play in reducing the high incidence of postharvest food losses, which is particularly high in perishable (horticultural) products, often reaching 50 to 80% of the total harvest, depending on the supply chain. While packaging practitioners point out the roles of packaging in enhancing a secure global food system, others are quick to point at the amount of packaging waste in dumps and landfills. Coles (2003) observed that less than 1% of packed food goes to waste, compared with 10 to 20% of unpacked food, quoting a Tetra Pak motto that says that a package should save more than its costs. On the other hand, a fairly recent supermarket survey in the UK reported that packaging adds 20% to the cost of fruit, in response to which the then Environment Minister Ben Bradshaw urged shoppers to boycott heavily packaged F&V in order to pressure supermarkets to be more environmentally friendly (Cecil & Widdup, 2007). So, I suggest that when it comes to environmental impact, packaging has an image problem, which raises the following crucial questions: Are we over-packaging? Are we under-packaging? Do we have sufficient scientific evidence demonstrating the roles and impacts of packaging on food security and environmental degradation? To reduce the environmental impact of horticultural packaging, it is equally important to ensure the ability of the packaging to reduce food waste that may result from physical damage and decay. Depending on the situation, especially where the environmental impact of the product is much higher, it may be necessary to increase the environmental impact of packaging in order to reduce food waste. The impact of imported packaging (containing imported products) may be subjected to more scrutiny by both the general public and policy officials. Given that perception can easily become reality, but more so because of public demand for corporate business responsibility, it is important that the packaging industry engages actively in research efforts to reduce both food and packaging waste.

- *Packaging standards: Who owns packaging?* – I have always thought about the number and types of packaging used in horticultural packaging. So far I am no closer to answers. Common questions have often been about why we have so many types and who decides what the appropriate packaging for the horticultural industry is. Obviously, different types and sizes of packaging are needed to meet market demand for the bulk and retail food trade. In the immediate future and with the demise of regulated single-desk export marketing, I do not see a quick resolution of the debate on the standardisation of horticultural packaging in the same product lines. However, it is more likely that major importers such as supermarkets and other global chains will continue to exert major influences within the relevant regional regulatory frameworks. Packaging used in international trade will continue to be highly influenced by global trends, standards and regulations.

■ *Ventilated packaging: A design response* – The expanding trade in and consumption of F&V and the need to maintain the product cold chain from farm to fork assure a future for ventilated packaging. By its nature, optimal vent design offers new opportunities to contribute to reducing the amount of packaging and food losses and increasing packaging cost-effectiveness. The combination of structural mechanics modelling with CFD modelling will become a powerful tool to resolve the oft competing demands of the cold chain and protection of perishable products against mechanical injury and spoilage during transport and distribution. This could make it possible to design packages that can hold fruit suspended in air cushions or other force-deceleration media inside a package, especially for soft fruit. The realisation of intelligent packaging in commercial supply chains will enable postharvest management of fruit quality at specific positions inside individual packages – enabling 'speaking fruit' to communicate with system controllers of environmental stress for response to relieve stress.

Finally, I see in the crystal ball that there are preconditions for the success of realising this kind of packaging in the future: sustained research and development to underpin new knowledge development, capacity building and the growing of own timber (both people and trees!) for the smart, intelligent, cost-effective and resource-efficient packaging of the 21st century.

CONCLUSION

Horticulture is an important part of the global food system, supplying a wide range of edible products (F&V, roots and tuber), ornamental plants and cut-flowers. International trade in horticultural products has grown dramatically, surpassing other agricultural commodities in value during the past 25 years. At present, food security is commonly expressed in terms of millions of tonnes of food grains produced or available. This orientation of food security focuses on the energy *availability* from foods and ignores the other equally important aspects of the food security complex – access and utilisation. Given research evidence on superior net farm income per family member of horticultural versus non-horticultural smallholder farms, and the fact that billions of people especially in Africa, Caribbean and Pacific depend on horticultural crops (such as roots and tuber, banana and plantains) as their major source of calorie intake (Opara, 2003), expressing food security status in alternative but broader indices such as *million person years of jobs and income* instead of quantity of food grains produced is perhaps more realistic. At community level and in non-grain producing regions, such a broad food security index would also highlight the relative contribution of horticulture and non-food sectors to food security at community and household levels.

Advances in innovative packaging have played a crucial role in making a wide range of quality and safe horticultural products available all year round and in locations far away from the region of production. Ventilated packaging has emerged as the dominant type of packaging used in the horticultural industry due mainly to the need to facilitate rapid cooling and maintain the cold chain. The evolution from hand holes to scientifically designed and rigorously tested vent holes progressed slowly due to the complexity of the geometry and fluid flow patterns inside the package. Recent advances in ICT, with increasing capacity at lower cost, and developments in CFD have made it possible to model and visualise fluid flow in such complex structural configurations. Building on the previous understanding of mathematical modelling of cold stores and heuristic models of fruit packaging, we have developed CFD-based models that allowed the prediction and visualisation of airflow patterns and heat transfer inside ventilated horticultural packaging.

Packaging has continued to play a critical role in the global food system – protecting produce, reducing losses and facilitating the availability of food far away from the point of production. However, like other industries, horticulture (and packaging) is also faced with the ongoing grand challenges facing humankind: climate change, food security and resource sustainability. These challenges have put a spotlight on packaging waste and food losses. As consumers continue to demand top-quality, safe and cheap food that is available all year round, produced and packaged in an environmentally responsible manner, there is a need for a radical rethink about the way we currently view, design and utilise packaging in the food system. Experimental design is expensive and time-consuming. CFD modelling, coupled with recent developments in nanotechnology and ICT, offers us a new and exciting innovative tool to develop the cost-effective and resource-efficient horticultural packaging of the future: *light, strong, cheap, recyclable and intelligent.* The need for engagement and dialogue among role players is ever more critical.

ACKNOWLEDGEMENT

I would like to thank Prof Lise Korsten at the University of Pretoria for her support and for inviting me to 'come back home' during our first meeting at a postharvest conference in Vietnam more than a decade ago.

REFERENCES

- Al-Ani, M.R., Opara, L.U. & Al-Rahbi, N. 2009. Fruit ripening stage affects lycopene and vitamin C content in tomatoes (*Lycopersicum esculentum*): nutritional and clinical implications. *Annals of Nutrition & Metabolism* 55 (S1):129.
- Amos, N.D. 1995. Mathematical modelling of heat and mass transfer and water vapour transport in apple coolstores. Unpublished PhD dissertation, Massey University, Palmerston North, New Zealand.
- Amos, N.D., Cleland, D.J. & Banks, N.H. 1993. Effect of pallet stacking arrangement on fruit cooling rates within forced-air precoolers. *Refrigeration Science and Technology* 3:232–241.
- Arnold, M. 1996. *Harvest and postharvest problems in agriculture, forestry and fisheries: The CGIAR contribution to research*. CGIAR Document No. SDR/TAC:IAR/96/5.
- Austin, J.E. 1995. Reflections on IDB strategy for agricultural and rural development. World Bank, Washington, DC, USA: Mimeo.
- Barron, M.A. & Rello, F. 2000. The impact of the tomato agroindustry on the rural poor in Mexico. *Agricultural Economics* 23:289–297.
- Bird, R.B., Stewart, W.Z. & Lightfoot, Z.N. 1960. *Transport phenomena*. New York: Wiley.
- Caleb, O.J., Opara, U.L. & Witthuhn, C. 2011. Modified atmosphere packaging of pomegranate arils: A review. *Food and Bioprocess Technology* DOI: 10.1007/s11947-011-0533-7.
- Cecil, N. & Widdup, E. 2007. *Evening standard*, 18 April. Available from http/www.thisismoney.co.uk/consumer/ [Accessed 30 December 2010].
- Coles, R. 2003. Introduction. In R. Coles, D. McDowell & M.J. Kirwan (eds.). *Food packaging technology*. Boca Raton: Blackwell, pp.1-31.
- Dodd, M., Cronjé, P., Taylor, M., Huysamer, M., Kruger, F., Lotze, E. & Van der Merwe, K. 2008. A review of the post harvest handling of fruits in South Africa over the past twenty five years. *South African Journal of Plant & Soil* 27(1):97–116.
- Elitzak, H. 1997. Farm value grew more than marketing costs in 1996. FoodReview, USDA's Economic Research Service, (September-December), 19: 28-32.
- Elitzak, H. 1996. Food cost review. AER-927. USDA-ERS, Food and Consumer Economics Division.
- FAOSTAT. 2011. http://faostat.fao.org/ Accessed 2 January.
- Ladaniya, M.S. & Singh, S. 2000. Influence of ventilation and stacking pattern of corrugated fibre board containers on forced-air pre-cooling of 'Nagpur' mandarins. *Journal of Food Science & Technology* 37:233–237.
- Nair, R.D. 2008. Food security in Africa: Challenges and interventions. *The Icfai Journal of Agricultural Economics* 1:61–76.
- Ngcobo, M.K., Opara, U.L. & Thiart, G. 2011. Effects of packaging liners on heat transfer and quality of fresh grape berries. *Packaging Technology & Science* (submitted).
- Nowak, J. & Rudnicki, R.M. 1990. *Postharvest handling and storage of cut flowers, florist greens, and potted plants*. Oregon: Chapman and Hall.
- Opara, L.U. 2004. A technological innovation triad shaping agriculture in the 21st century. Part 1: Nanotechnology. Invited overview paper, Agricultural Engineering International – the CIGR Journal of Scientific Research and Development, vol. 6: 1-27.
- Opara, L.U. 2003. Postharvest technology of root and tuber crops. Chapter 15. In: R. Dris, Raina Niskanen and Shri Mohan Jain (ed), *Crop Management and Postharvest Handling*, Oxford & IBH Publishing Co., pp. 379-404.
- Opara, U.L. 2010. Making every harvest count: the role of postharvest research in development. *South African Fruit Journal* 8(6):33, 35.
- Opara, U.L. 2009a. Building human capacity for our future. *South African Fruit Journal* 8(4):25–26.
- Opara, U.L. 2009b. Challenging our postharvest technology research and innovation system. *South African Fruit Journal* 8(5): 25-26.
- Opara, U.L. 2009c. Modelling cold chain technologies: An engineering perspective. Invited paper presented at the International Workshop on Innovation: Development and Trends, 13–15 July, Pretoria, South Africa.
- Opara, U.L. 2009d. Preharvest, postharvest handling and processing effects on Zinc content of food. Invited keynote presentation at the International Conference on Effect of Zinc Fertilisation on Nutrition and Food Quality, 26–27 March, Windsor Hotel, Nairobi, Kenya.
- Opara, U.L. 2009e. Quality management: An industrial approach to produce handling. In

W.J. Florkowski, R.L. Shewfelt, B. Brueckner & S.E. Prussia (eds.). *Postharvest handling: A systems approach*. Second edition. Amsterdam: Elsevier, 154–204.

- Opara, U.L. 2009f. Quality measurement in postharvest research: Opportunities for collaboration in IR spectroscopy. Invited paper presented at the Intervitis/Interfructa and South African Society for Oenology and Viticulture Conference, 28–31 July, Cape Town, South Africa.
- Opara, U.L. 2009g. The role of postharvest horticulture on total food security in Africa. Paper presented at the All Africa Horticultural Congress, 31 August – 3 September, Nairobi, Kenya.
- Opara, L.U. 1995. The cost of fruit. Unpublished report. Massey University, Palmerston North, New Zealand.
- Opara, L.U. and M.R. Al-Ani. 2010a. Antioxidant components in fresh-cut and whole fruit and vegetables. *British Food Journal*, 112(8): 797-810.
- Opara, U.L. and M.R. Al-Ani. 2010b. 2010. Effects of cooking methods on carotenoids content of Kingfish. *British Food Journal,* 112(8): 811-820.
- Opara, L.U. & Q. Zou. 2007. Sensitivity analysis of a CFD modelling system for airflow and heat transfer of fresh food packaging: Inlet air flow velocity and inside-package configurations. *International Journal of Food Engineering*, 3(5): article 16.
- Rizvi, S. 2010. Role of food processing in international agricultural development. Cornell: Department of Food Science, Cornell University.
- Siegruhn, R. 2010. Value chain costs and profits in a citrus supply chain. Personal communication: Paarl, South Africa.
- Singh, D., Mandal, G. and Jain, R.K. 2005. Effect of ventilation on shelf life and quality of peaches. Acta Hort. (ISHS) 696:519-522.
- Tanner, D.J. 1998. Mathematical modelling for design of horticultural packaging. Unpublished PhD dissertation, Massey University, Palmerston North, New Zealand.
- Tanner D.J., Cleland, A.C. & Opara, L.U. 2002. A generalised mathematical modelling methodology for design of horticultural food packages exposed to refrigerated conditions. Part 2: Heat transfer modelling and testing. *International Journal of Refrigeration* 25(1):43–53.
- Tanner, D.J., Cleland, A.C., Opara, L.U. & Robertson, T.R. 2001. Use of CO_2 as a trancer gas for determing in-ackage airflow distribution. *Journal of Agricultural Engineering Research* 77(4):409–417.
- Tanner D.J., Cleland, A.C., Opara, L.U. & Robertson, T.R. 2002. A generalised mathematical modelling methodology for design of horticultural food packages exposed to refrigerated conditions. Part 1: Formulation. *International Journal of Refrigeration* 25(1):33–42.
- Tanner D.J., Cleland, A.C. & Robertson, T.R. 2002. A generalised mathematical modelling methodology for design of horticultural food packages exposed to refrigerated conditions. Part 3: Mass transfer modelling and testing. *International Journal of Refrigeration* 25(1):54–65.
- Tassou, S.A. & Xiang, W. 1998. Modelling the environment within a wet air-cooled vegetable store. *Journal of Food Science* 38:169–187.
- Wang, H. & Touber, S. 1990. Distributed dynamic modelling of a refrigerated room. *International Journal of Refrigeration* 13:214–222.
- Weinberger, K. & Lumpkin, T.A. 2007. Diversification into horticulture and poverty reduction: A research agenda. *World Development* 35(8):1464–1480.
- Xu, Y. & Burfoot, D. 1999. Simulating the bulk storage of foodstuffs. *Journal of Food Engineering* 39:23–29.
- Yahia, E.M. (ed.). 2009. *Modified and controlled atmospheres for the storage, transportation, and packaging of horticultural commodities*. Boca Raton: CRC Press.
- Zou, Q. 1998. CFD modelling of airflow and heat transfer in a ventilated carton. Unpublished MApplSc thesis, Massey University, Palmerston North, New Zealand.
- Zou, Q., Opara, L.U. & McKibbin, R. 2006a. A CFD modeling system for airflow and heat transfer in ventilated packaging during forced-air cooling of fresh foods. I: Initial analysis and development of mathematical models. *Journal of Food Engineering* 77:1037–1047.
- Zou, Q., Opara, L.U. & McKibbin, R. 2006b. A CFD modeling system for airflow and heat transfer in ventilated packaging during forced-air cooling of fresh foods. II: Computational solution, software development, and model testing. *Journal of Food Engineering* 77:1048–1058.