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Determining the quality of leafy salads: past, present and future

Jake Jasper, J. Stephen Elmore, Carol Wagstaff.

Department of Food and Nutritional Sciences, University of Reading, Whiteknights, Reading RG6 6DZ, UK.

Abstract

The relatively high proportion of avoidable waste from leafy salads and the under-consumption of fruits and vegetables generally is contributing toward renewed interest in the value of on-pack dates, particularly those that indicate quality. Current methods of predicting shelf-life in fresh vegetables and salad are relatively conservative due to the high variability of the product and few reliable markers that can be used to predict shelf-life. This is evidenced by the proportion of wastage in this category where fresh vegetables and salad account for almost a quarter of all avoidable food waste by weight. We have looked at the historical context in which date markings have been derived, how they function currently and look at how the current system could be improved. We review the three primary factors that influence the quality of a product – microbiology, visual quality, aroma – and suggest that if more accurate predictions of shelf-life are to be obtained non-destructive methods of testing need to be developed in order to provide the consumer with accurate information about the current state of the product.

Keywords: shelf-life; salad; non-destructive; waste.

1. Introduction

1.1 *The fresh produce industry*

Fresh produce is a category that encompasses farmed horticultural products, most commonly fruits and vegetables. Globally the yield and value of this sector has been increasing steadily over the last decade, and this trend is set to continue. From 2008 to 2018 global vegetable production increased from 4.4×10^8 to 6.4×10^8 tonnes and was forecast to maintain this growth (Euromonitor International, 2019). In Europe, 2.2 million hectares of land were used to produce fresh vegetables with nearly half coming from just three countries: Italy, Spain and Poland. Within that, approximately 17.8 % of the land is used for leafy and stalked vegetable production (De Cicco, 2016). The United Kingdom (UK) dedicates 78,000 hectares to vegetable and salad production (DEFRA, 2018a).

In the UK, which historically has one of the highest consumptions of fruit and vegetables in Europe (Eurostat, 2018), 46 grams of leafy salads were purchased per person per week (DEFRA, 2018b). In the last decade, the number of prepared leafy salad items purchased has doubled in the UK from a spend of 519 to 1100 million pounds showing an increase in the desire to consume more conveniently prepared leafy vegetables as part of a balanced diet (Kantar World Panel, 2018). The desire for more leafy vegetables, along with increases in population, has resulted in a significant increase in importing leafy vegetables to the UK over the last couple of decades (Figure 1).

[Figure 1]

1.2 *Challenges facing the fresh produce industry*

There is a mounting pressure on the entire global food system to increase sustainable food production, to cope with the growth in population numbers and the dietary changes that occur as populations become more affluent (Gerbens-Leenes et al., 2010). It is estimated that food production will have to increase by 70% by the year 2050; not only will it have to increase in volume, but also in safety and nutrition (SEC(2010)379).

Alongside pressure from an increasing population, there are guidelines from governments and health organisations to increase consumption of fruits and vegetables. The World Health Organisation (WHO) recommends that people consume 400 g of fruits and vegetables per day to improve overall health. However, this goal is not commonly achieved (EUFIC, 2012). Increased production of fruits and vegetables is one part of the solution, another is increasing the consumption of those which have been grown, harvested and purchased. The majority of food waste in countries with highly developed food chains occurs with consumers, and the longer the consumer keeps the food after purchase the less likely they are to consume it (Porat et al., 2018). As the produce ages the consumer views it as less valuable, due to its perceived decline in quality and safety. Often food that is acceptable to eat is wasted; in the UK in 2012 it was estimated that 37.8% of leafy salad purchases ended up as avoidable waste (Quested and Murphy, 2014).

Food waste is a multifactorial problem and losses are not always avoidable. However, there are many aspects to improve on and these are covered by Sustainable Development Goal 12.3 (FAO 2019). One particularly important area is on-pack dates. In the majority of cases, where a date is present on the pack (best-before or use-by) it is indicating either safety or quality of the pack contents. With respect to safety there are robust scientific methods that are used to define the date, although a margin of error is usually applied, which itself may increase waste. With quality the consequences of errors are less serious for consumer health and, as such, the ways in which the dates are derived are often quite rudimentary. This leaves larger margins for error and can potentially mislead the consumer, causing them to discard the salad when it is still safe to consume. Approximately 70 % of the time consumers use on-pack dates to decide whether or not a salad is ‘okay’ to consume. Similarly, the appearance is also cited as a deciding factor 70 % of the time; in contrast, less than 10 % of respondents said that smell was used (Lyndhurst, 2008). This highlights the importance of providing accurate information to the consumer and that consumers often rely on visual cues when evaluating a product. The situation is further complicated by the fact that consumers often open the bag and consume some of the product immediately afterwards, but then often keep the remainder for another day. The combination of changing the gaseous atmosphere inside the bag and manual handling of the leaves often renders the ‘use-by’ date aspirational, to the extent that some suppliers advise that bags are guaranteed until the ‘use-by’ date or 24 hours after opening the bag, whichever is soonest. Educating sustainability-minded consumers about what constitutes real deterioration may help to alleviate some of the waste that occurs when consumers throw away product prior to the end date on the pack. Equally, encouraging disposal of waste salad into compost rather than landfill will have benefits for sustainability in the home. Retail waste can be on a much larger scale, for example when shelves are stacked with salad products in anticipation of good weather, only to find that unseasonable rain and cold weather (a common feature of a UK summer) drives consumers away from salad purchase. In these cases developing better systems for collection and valorization of wasted leaves and packaging are needed to improve sustainability goals.

One of the biggest barriers the industry has to being able to provide accurate information to the consumer is the lack of reliable tests for markers of quality (Spadafora et al., 2016; Tsironi et al., 2017), and those that do exist measure the current status of the product rather than providing any predictive information relating to shelf-life (SL). As a consequence, the quality indication given by use-by dates is often tenuous; furthermore, when it is suspected that quality will be diminished and a shorter SL is required, there is little evidence to back this up and the date on pack often stays the same regardless of what quality assessments were made at harvest or at factory intake.

This review will explore the options available to suppliers and retailers that would help reduce the volume of food loss and waste that occurs in the ready-to-eat salad industry. This will include an evaluation of the technologies available for predicting shelf life of the leaves before they are packed, ways of dynamically assessing quality loss during shelf life, and advice that may be given to consumers that would help prevent food waste from bagged salads in the home.

2. Shelf-life: brief history and definitions

2.1 *A history of shelf-life legislation*

As long as there has been trade there have been rules and customs. Early food law was primarily concerned with food adulteration (Sophia, 2014). With the rise of centralised distribution in the food supply network starting in the 1970's more advanced methods of stock control were required (Moore, 1991). Marks and Spencer introduced sell-by dates in the UK in 1973 to keep track of stock (Marks and Spencer, 2020), but that was not intended to convey information to the consumer. It was not until 1980 that there was a statute requiring dates to be included on packaging informing consumers of quality. A date of 'minimum durability', now commonly known as 'best before', was introduced in the UK (SI1980/1849) soon after similar legislation (79/112/EEC, 1978) was introduced to the European Economic Community (EEC). Use-before dates were introduced in the same document, and later revised to the wording 'use-by' (89/395/EEC, 1989). A year later the UK introduced use-by dates into its own legislation in an amendment to the Food Labelling Regulations (SI 1984/1305, 1984). The introduction of a date of minimum durability was first discussed by Codex Alimentarius in 1965, where the committee agreed with a statement from the UK delegates (ALINORM 65/22, 1965):

'Much depends on the quality and freshness of ingredients and on distribution and storage conditions.'

The next mention of a date of minimum durability was in 1972 when a standard list of date markings was discussed, to consolidate the markings being used (ALINORM 72/22, 1972). The first appearance of the definition in a similar form as it is today was presented by the Federal Republic of Germany:

"*If the minimum durability date was applied in such a manner so that foods exceeding the date and which are still in good condition were not removed from the market, then both the producer and the consumer would benefit, the latter in terms of possibly lower priced foods.*" (ALINORM 74/22, 1974).

They also stated that: "*without such an application of this type of date marking provision, the risk existed of restricting distribution to the larger, higher volume retailers.*"

However, in the UK the attitude was still of the view that the date of minimum durability was unnecessary other than for stock control purposes, and that minimum durability was 'open to interpretation', and argued that the SL would be variable depending on the storage conditions used by the consumer (Sawyer et al., 1980). The best-before date remains controversial (Neff et al., 2019) and the definition is still being discussed (REP18/FL, 2018).

[Figure 2]

2.2 Legal definitions relating to shelf-life

The European Union set out two different formats for on-pack date labels; the first, 'use by', is for products that are likely to be injurious to health at a certain point in time. The second date label is the 'date of minimum durability', or 'best before' which is the 'date until which the food retains its specific properties when properly stored' (1169/2011). These static dates on the packs of fresh produce can be considered the SL of the produce within. However, 'shelf-life' is not specifically used in EU labelling legislation, but it does appear in (2073/2005) related to the microbiological criteria of food (Article 2,f):

> *"'Shelf-life' means either the period corresponding to the period preceding the 'use by' or the minimum durability date, as defined respectively in Articles 9 and 10 of Directive 2000/13/EC."*

The words 'Shelf-life' do appear in a statuary instrument in the UK, but the definition refers to 'use-by' and 'best-before' definitions in EU legislation (SI 2014/1855).

Unlike other categories in the food industry, the fresh produce industry has limited options when it comes to food processing and preservation. Because of this, the life of fresh produce is particularly short post-harvest. This is certainly true of leafy salads, where products are not expected to last longer than two-weeks post-harvest (Tsironi et al., 2017; Bell et al., 2017). The most significant reason for accurate communication of SL by a use-by date is ensuring microbiological safety. Any product designated as RTE must carry a use-by date (EC 2073/2005) and, since bagged salad leaves are usually in this category, the suppliers do not have a choice but to impose a use-by date rather than a best-before date. It is a criminal offence to sell food that has passed its use-by, but this is not true for food that is past its best-before date (178/200, 2002) although retailers often do not sell food past its best-before date.

Although leafy salads are required to have use-by dates, some products carry a best-before date where it is assumed further processing, e.g. cooking, will occur in the home – for example with products such as sliced kale or spinach. This leads to some anomalies in the current retail system: spinach sold as a single line bagged salad is classed as RTE and is subject to a 'use-by' date. The same type of leaf is sold as a different line with other leafy green vegetables that are marketed for cooking and therefore has a 'best-before' date on pack. Since there is nothing to stop a consumer using a vegetable spinach in a salad, or blending sliced kale into a smoothie, it is clear that the distinction between use-by and best-before is a somewhat artificial construction that doesn’t necessarily protect consumers who are consuming them raw from microbiological safety breaches. Best-before dates are set to give the consumer an indication of the decline in the quality of the product. As the decline in quality is a result of decay and senescence, which are biological processes, there are many different inputs and pressures that influence the decline. Variance in salad crops are attributed to differences in growing conditions such as light intensity (Fu et al., 2012), and irrigation strategy (Luna et al., 2012; Allende and Monaghan, 2015). As well as the agronomic inputs, the genetic factors such as species and cultivar, influence the variability in the post-harvest longevity of the product (Ntsoane et al., 2016; Bell et al., 2017; Jasper et al., 2020). Furthermore, as the leaves of the plant mature at different rates, there will be significant differences in the quality of leaves from the same plant. Because of this, the quality of the leaves within the individual bags may be highly variable. All of the pre- and post-harvest factors make accurately assessing a product's SL difficult, and interplant variability is one of the biggest challenges.

Commercially, all produce within a particular plot of land is planted and harvested at the same time. Within the plot there will inevitably be some variation in rates of growth and development, plus there will be leaves of different developmental stages within the same plant. Therefore, leaves of different maturities are harvested together, meaning that the physiology and chemical composition will be different between leaves in the same bag. Whenever a ready-to-eat (RTE) salad bag is assessed the SL will be based on the average for all the leaves within the pack. This variation increases the difficulty in defining SL, and as to why the date on packs is set conservatively.

Suppliers of fresh produce will choose a use by date that is a set number of days after the produce is packed. This date has a margin of error, perhaps two days, and this interval will stay static throughout the year, with the occasional adjustment downwards if the crop is known to have a significant reduction in quality. Therefore, the date on the pack is set to cover the worst-case scenario, which is good for ensuring public health, but sub-optimal for minimising waste (Lee et al., 2015). Food waste associated with these products could be mitigated by retail and domestic purchasers with better planning and logistical tools (for retailers) to improve the relationship between supply and demand. However, with current supply chains requiring several days between harvest and point of sale, and with rapidly fluctuating weather conditions driving very short-term fluctuations in what consumers choose to eat with a crop that takes several weeks to develop from sowing to harvest, managing supply to consumption patterns is challenging. Alternative supply chains are discussed in the section below that may enable shortened crop cycles and more localised supply chains that may both improve quality and reduce waste.

There is a vast amount of literature assessing different facets of fresh-produce physiology and biochemistry over SL (e.g. Wagstaff et al., 2007; De Corato, 2020). However, there is a disconnect between the information gathered in academia, and the dates that are placed on the packs of consumer goods. This is often because the advanced methods used in academia do not translate to industry, due to practical, economic and technological constraints. Moreover, studies are rarely repeated across the seasons and varieties appropriate for an individual type of crop. Hence, markers may be indicative of SL under a certain set of conditions but as conditions change these markers often do not produce generalised values in a way that is useful for industry to adopt.

There are many ways of quantitatively assessing quality attributes that are linked to SL. The challenge for those wishing to implement such measures is that the underpinning biology that regulates leaf degradation and quality loss is highly variable depending on factors linked to plant development, agronomy and post-harvest handling. The following sections explore quality attributes linked to SL, providing information on the biological factors underpinning the measurable symptoms, methods for quantitatively analysing each factor or its symptom, and a review of available technologies that can currently predict the development of a quality marker.

2.3 *The supply chain of RTE leafy salads*

The food supply chain for ready to eat or ready to cook cut fresh vegetables can be rather long, given the delicate nature and cellular vulnerability of these plant products. For example, if a product is grown in southern Spain for consumption in the UK it can be 24h between harvest and starting its journey, during which time it is imperative to remove the field heat from the crop as rapidly as possible (Bell et al., 2017) and to thereafter keep it at optimal storage temperature so that metabolic processes are arrested without causing chill damage. It can take three days to transport the crop by road to the UK, with temperatures often highly variable between different parts of the lorry. On arrival in the UK the crop may spend another 24-48 hours being washed, processed and packed before it is distributed to a retail outlet. Typically a use by date on pack can be five to seven days after packing, meaning that the product has to meet quality threshold criteria relating to appearance, safety and organoleptic characteristics for at least ten days after harvest. Therefore, the care with which the product is handled and the integrity of the cold chain through which the product moves after harvest is absolutely critical to its ability to meet quality and safety requirements.

Sub-optimal storage conditions can lead to increased quality and safety issues because the storage temperature will influence the rate of respiration and the rate of microbial growth (Løkke et al., 2012; Alongi et al., 2019). With a longer supply chain, there is a greater potential for temperature abuse which can be detrimental to the product and increase the rate of deterioration. The longer the product takes to get to the retail shelf after packing, the less time the consumer has to enjoy the project before it reaches the end of shelf-life. Whilst there is encouragement to reduce the length of supply chains and grow more of the crop in the country where it is going to be consumed, e.g. through indoor farming, it will be many years before these initiatives can account for a significant portion of the ready to eat/ready to cook vegetables that are currently produced in Europe for consumption elsewhere. It is therefore valuable to continue to apply effort to improving cold chain management and to innovations in packaging that lead to increased quality of the product at the point of consumption.

3. Microbiology and shelf-life

With respect to SL, safety is the most important factor. The ‘use-by’ date, which is defined in relation to microbiological safety, is in place to protect the consumer. It is an offence to sell any product past its stated ‘use-by’ date. For leafy salads, the control of micro-organisms is one of the primary concerns; this is because of the relatively limited processing options available. Traditionally, salad vegetables do not carry any form of date as they are often unpackaged. However, with rising demand for convenience, leafy salads are increasingly being sold as RTE. Any product designated as RTE must carry a use-by date (EC 2073/2005). Often, a product that will be sold as RTE is further processed for added value – cut into portions, for example. As RTE products are not going to be further processed by the consumer, they must be safe to eat within a stated timeframe. There are very severe consequences, both financially and reputationally, for a business if there is a food poisoning outbreak from their product (Koukkidis and Freestone, 2018). As a consequence of having relatively few tools to ensure safety and severe consequences of injuring the consumer, the date on the pack is often a conservative estimate.

3.1 *Causative agents of microbial problems*

At every stage in the supply chain, there is an opportunity for micro-organisms to contaminate food. Often the environment in which the food is produced, be it open-field or hydroponic for example, or the properties of the foodstuff itself are determinants of which micro-organisms will develop (Söderqvist, 2017). There are three micro-organisms that have specific regulations pertaining to the safety of leafy salads; these are *E. coli* 0157:H7, *Listeria monocytogenes* (LM), and *Salmonella* (Table 2). *Salmonella* and LM have regulations that are in place while the product is on the shelves. In contrast, the law for *E. coli* is only applied during the manufacturing stage, as although it can be injurious to health, it is not known to grow on leafy salads under RTE conditions (Abdul-Raouf et al., 1993). Although there is evidence that LM and *Salmonella* can grow at chilled temperatures, these organisms are not generally considered to contribute to the spoilage of the salad product (Horev et al., 2012). These organisms are important with respect to SL. However, we are primarily focused on quality changes and therefore, they shall not be discussed in detail in this review.

Micro-organisms are part of the many factors that contribute to the spoilage of food. However, as with many processes in biology, no single factor is entirely responsible as physical, chemical and microbiological factors all contribute. Bacterial spoilage is often associated with slime and a watery appearance (Tournas, 2005) caused by the formation of biofilms and/or by breakdown of the underlying leaf material. In addition to producing mycelium and spores, fungi have also been associated with a watery appearance, therefore the causal organism of similar symptoms is not always straightforward to identify by appearance alone. Unsurprisingly, the species or micro-organisms that are able to survive and even replicate at refrigeration temperatures are most commonly associated with food-spoilage such as those belonging to the *Erwinia* species.

Routine testing for food spoilage organisms is not standard practice. This may be due to the economics of administering these tests, the lack of guidance on testing the less frequently occurring organisms, lack of knowledge about the relationship between organism load and the prevalence of symptoms, or lack of knowledge about the underpinning colonisation and disease development to provide informative predictive or actionable data.

3.2 *Evaluation of microbial load*

There are legally defined microbiological sampling and testing methodologies for establishing SL (EC 2073/2005, 2006). Because of this, microbiology is unique as a measure of quality in that the same criteria that establish the date on the pack are the same for every product that is sold within a particular jurisdiction. The standard methodology for assessing the microbiology of a product is defined in Commission Regulation 2073/2005 (2006), where the specific ISO method for testing is referred to. Aerobic Colony Count (ACC) is often used; thresholds vary for what is classed as unacceptable, but are usually in the range $10^5 – 10^7$ colony forming units per gram (cfu/g) (Health Protection Agency, 2009; Calonica et al., 2019). Values in excess of this figure suggest the microbial flora is considered to be from one predominant organism (Health Protection Agency, 2009).

When measuring the microbiology over SL in RTE products, samples are taken at the start of production and at set points throughout the SL period. Organisms that are relevant to the safety of RTE salads are highlighted in Table 2. Often the product is on the shelves before the results of the tests are known as the current testing methods usually require 48 hours of incubation time. So, if the results come back positive for pathogenic micro-organisms, products have to be removed or recalled depending on how far they have made it through the supply chain. A lot of research has been undertaken to try and develop novel non-destructive methods of quantifying micro-organisms and the majority of these methods are based around imaging techniques (Pan et al., 2018; Herrero-Langreo, Scannell and Gowen, 2020).

For a method to be truly useful at assessing microbial accumulation during SL it has to enable measurements to occur while the product is still in its packaging, and for organisms related to spoilage there has to be some knowledge of what level of abundance should indicate a cause for concern. To the best of the authors' knowledge, there are no implementations of such as system. There are commercialised methods for the detection of various aflatoxins in nuts and dried fruits, but there are yet to be similar methods in the fresh salad industry (Yanniotis et al., 2011; Wu, Xie and Xu, 2018). It is usual to see higher aerobic colony counts in products that have not been stored adequately. Due to the logistics of the supply chain, the retail environment, and the minimal processing options, leafy salads often have unsatisfactory numbers. Calonica et al. (2019) found that only 8.3% of samples of salads taken from retailers were satisfactory ($< 10^5$ cfu/g) and by the end of shelf-life 80% of samples were unsatisfactory ($> 10^7$ cfu/g). ACC gives an indication of the overall microbial status of the product and is not suitable as an indicator of specific organisms. As the microbial status of a leafy salad is often unsatisfactory, and that there are relatively limited options for controlling and monitoring micro-organisms, there is a large amount of work in research and development for discovering methods that can reduce microbial load and still deliver the quality of product that the consumer demands.

3.3 *Preventing microbe-derived quality loss*

Controlling micro-organisms on leafy salads affords far fewer technologies than most other food categories, since thermal treatments, which are well developed, are not feasible on salad leaves due to the perishability of the crop. There are numerous ways in which growth of micro-organisms can be controlled, and it is a highly active area of research, reflecting the economic importance of this problem (Costa et al., 2011; Mogren et al., 2018). There are broadly two different approaches to controlling micro-organisms, physical and chemical.

3.3.1 *Physical methods of preserving fresh produce*

Physical methods of controlling micro-organisms, apart from heat treatment, include treatments such as modified atmosphere packaging (MAP) and radiation-based techniques. Ultraviolet (UV) light has been studied in its application at reducing the microbial load on leafy salads, and has been found to be effective (Ignat et al., 2015); however, there is the possibility of damaging the leaves with high levels of exposure. The UV radiation disrupts DNA replication and transcription in its germicidal action, but its action can also cause quality defects such as increased respiration, which is unfavourable as far as storage life is concerned, and in strong enough doses can physically degrade the leaves (Martínez-Hernández et al., 2015). Irradiation techniques using gamma radiation have been approved for use on lettuce and spinach in the USA by the FDA (Goodburn and Wallace, 2013), and have been shown to be effective in many studies (Chun et al., 2010; Olanya et al., 2015). However, there is conflicting evidence from RTE salads whether these types of treatment persist through shelf-life or just exert their effect as a one-time decontamination (Goodburn and Wallace, 2013). There does not seem to be a large take-up of this technology in the fresh produce industry, partly due to economic factors, but also due to consumer concerns over irradiated produce (Bearth and Siegrist, 2019).

Modifying or regulating the atmosphere inside the packaging of a product has been used extensively within the fresh produce industry, and there are many reviews on the topic (Caleb et al., 2013; Hussein et al., 2015). Typically, in MAP varying combinations of nitrogen, oxygen and carbon dioxide are used depending on the product. Noble gases, which have low reactivity and no odour, have also been investigated in combination with ‘traditional’ gases and found to be effective in maintaining the quality of rocket (Char et al., 2012). However, in the same paper it was also reported that argon-enriched atmospheres increase respiration around 15%, which may reduce SL. The modified atmosphere is achieved either by gas flushing to displace the air inside the bag with a desirable composition of nitrogen (or other noble gas), oxygen and carbon dioxide (active MAP) or by using microperforations in the packaging to balance the respiration rate of the product with gas exchange between the internal headspace and the external environment (passive MAP). Passive MAP can take several days for equilibrium to be reached and, in both cases, the evolution of the internal atmosphere is dependent on factors controlling the respiration of the fresh product, e.g. temperature. If the permeability or environmental conditions are not optimised then the quality of the product will be severely compromised (Ares et al, 2008). There are many studies that show the attenuation of micro-organisms using modified atmospheres (Ioannidis et al., 2018; Kapetanakou et al., 2019). However, once the pack is opened the benefits of the MAP are lost. There are several packaging parameters that affect the atmosphere within the bag, including film thickness, number of perforations, orientation of polymer chains and polymer type. For packaging of leafy salads polypropylene is the most common polymer, but the packaging parameters will vary depending on the product. The atmospheric conditions in MAP, which are usually low O_2, CO_2 and high nitrogen compared to atmospheric composition (Campbell-Platt, 2017) can give rise to negative quality aspects such as discolouration and off-odours (Nielsen et al., 2008; Tudela et al., 2013). However, there are concerns over the sustainability of some of the materials used to package RTE salads, with recycling options severely limited. There is pressure to develop biodegradable, compostable or more easily recyclable packaging options that still retain the ability to control quality of the plant material within (Roohi et al., 2018).

3.3.2 *Chemical methods of preserving fresh produce*

Chemical methods of controlling micro-organisms are far more numerous, which may reflect the commercial viability of these methods for controlling micro-organisms. As vegetables tend to be washed to remove soil and debris, it makes practical and economic sense to use this stage to sanitise the produce for micro-organisms. Simply washing the produce in chlorinated water remains one of the most common practices when it comes to controlling micro-organisms on fresh produce. However, questions have been raised as to whether or not the results from chlorine washing are significantly different to washing with water alone (Luo et al., 2011) and there has been increasing pressure from regulatory authorities to reduce or remove chlorination from RTE products (Uhlig et al., 2017). There are many alternatives to chlorine, many of which are based on weak organic acids such as citric, malic and tartaric acid. The use of weak organic acids is based around overwhelming the ability of bacteria to remove protons from their cell interior and therefore not being able to effectively reproduce as they have to expend energy pumping out protons from their interior (Akbas and Ölmez, 2007). There are many examples of different chemical combinations in the literature, with different modes of action such as thymol or carvacrol, which are both thought to increase the membrane permeability of bacteria through interactions of the phenol group and its destabilised electrons with the cell membrane (Zhou et al., 2007). Peroxyacetic acid produces reactive oxygen species which can damage DNA and lipids of bacteria; furthermore, it can denature proteins and enzymes by oxidising disulphide bonds which also increases membrane permeability (Vandekinderen et al., 2009). Cuggino et al., (2020) found that benzyl isothiocyanate (BITC) was synergistic when combined with chlorine to increase the effectiveness of decontamination over chlorine alone. Although they did state that the results may have been due to the change in the pH rather than the antimicrobial properties of the BITC. Other plant-derived compounds such as *Origanum vulgare*, which is derived from oregano, has been shown to be effective in reducing *E. coli* O157:H7 packed spinach and lettuce when combined with traditional sanitisers such as sodium hypochlorite (Poimenidou et al., 2016). Novel plant-derived compounds such as BITC, oregano extract and organic acids are desirable not only for their effectiveness at decontaminating salad leaves but also because they are not required to be stated on the label as they are generally regarded as safe (GRAS) and or classified as processing aids. This is an advantage as consumers are wary of decontaminants (Aoki et al., 2010). Ultimately it comes down to price and, if not already approved, getting the product approved by governing bodies; many of the alternatives to chlorine are not economically competitive.

3.3.3 *Nanotechnology and its role in food packaging*

The incorporation of nanomaterials into food packaging is an area of research that is in the ascendency. Antimicrobial elements such as silver are being incorporated into packaging with success (Costa et al., 2011). However, as the technologies surrounding the use of nanomaterials is developing, the regulatory authorities have yet to form a consensus as to the efficacy and safety of many of the technologies and, therefore, few examples exist within the food industry (Eleftheriadou et al., 2017). This is particularly true of the use of heavy metals, such as silver, which can have detrimental effects on human health and the environment (Tóth et al., 2016). One of the concerns with incorporating sensors or nanomaterials into packaging is the effect on the recyclability of the packaging; reducing food waste at the cost of increasing packaging waste is not a desirable trade-off.

[Table 2]

3.4 *The influence of seasonal and agronomic factors on microbial quality*

One of the many reasons why it is hard to predict the SL of a product is due to the fluctuating environment in which the product is produced. The majority of leafy salads are grown in open-field;

therefore, weather and seasonality play a role in determining the microbiological safety and the quality of the product. Caponigro et al., (2010) looked at six different RTE salad products from Italian supermarkets over two years and found that microbial loads peaked in the autumn months. It has been suggested that during periods of higher rainfall bacteria are better able to spread and be carried to different locations which may be a more of a factor than temperatures in accounting for the differences between seasons. However, the variability in bacterial loads is not consistently higher in the autumn/winter months. Rastogi et al., (2012) found that there was a one-log decrease in culturable bacteria of lettuce grown in the winter season compared to the summer season. It is more likely that high rainfall leads to more soil splash onto the leaves and contamination through that more immediate route, rather than transfer in moisture-dense air between fields. Often it is atypical weather events such as high rainfall and flooding that are positively correlated with increased microbial contamination (Medina-Martínez et al., 2015), supporting the hypothesis that bacteria are transferred from the soil to the leaves. This is a particular concern when considering climate change and its potential for increased variability in weather conditions and the frequency of which extreme weather events occur (Liu et al., 2013).

Leafy salad crops that are field-grown have many more avenues for contamination than those that are grown in soil-less systems. Field-grown crops may also be exposed to contamination from livestock in surrounding fields, wild animals, standing water or manure fertiliser. In contrast, produce that is grown under-protected and/or soil-less systems, such as hydroponics, is able to be more tightly controlled. Manzocco et al., (2011) found that hydroponically grown lamb's lettuce did indeed result in a lower microbial count (Total Coliform and Pseudomonas) when compared with a soil-grown crop. However, there was no difference in Enterobacteriaceae, which hydroponically grown crops are also susceptible to as these organisms are typically found in contaminated water supply and can enter the plants via the roots (Lenzi et al., 2021).

As well as the variation from seasonal influences, and that of the growing environment, the plant maturity also has an impact on the SL of the product. A consistent finding is that immature leaves tend to have higher respiration rates than mature leaves. Higher respiration rates potentially reduce SL as the leaves may degrade quicker than those with lower respiration rates (Martínez-Sánchez et al., 2012; Hunter et al., 2017). It has also been observed that immature leaves have higher microbial counts than those that are at harvest maturity (Rastogi et al., 2012; Williams et al., 2013; Dees et al., 2015). It is has been suggested that as the plant matures, selective pressure on micro-organisms occurs which accounts for the decrease in micro-organisms present on mature leaves, but this has not been proven, and often the seasonality effects are a confounding factor. The many different factors that can influence the microbiology of salad leaves make forecasting how the safety and quality of a product will change throughout the year challenging. As it is difficult to predict how micro-organisms develop on salad crops from the growing stage, processing the leaves and storage in the consumers home, SL dates are often conservative to minimise the chance of ‘injuring the consumer’ at the expense of increasing waste.

3.5 *Modelling and predicting microbial growth*

The importance of keeping the consumer safe and meeting the quality standards that they expect are top priorities, because of this, predicting the growth of micro-organisms is a well-studied area. Typically, there are three classes of predictive modelling: primary modelling, where a few kinetic parameters are measured such as lag time or growth, and a growth rate with respect to time is calculated; secondary modelling, which incorporates environmental variables such as temperature and their effect on the parameters from the primary model; tertiary modelling, which are consumer friendly packages designed for food business operators to be able to produce models of microbial growth, evaluate the safety of their products, and inform SL estimation. ComBase (https://www.combase.cc) provides links to many of these software packages. These models allow food businesses to estimate levels of micro-organisms at the time of consumption and factor in many different variables such as temperature, pH and preservatives (Psomas et al., 2011).

Often there are many different variables in the food supply chain that can affect the growth of micro-organisms, which are not captured within these models. The consequence of this is that companies will apply a conservative margin of error on the use-by date, of at least two days, which may reflect the lack of confidence in the underlying model. The length of time it takes for the product to reach the shelves after packaging is not always predictable and therefore providing for this also contributes to conservative labelling. There are always going to be errors in predictive modelling as it is not feasible to take all possible scenarios into account. The margin of error is applied to avoid human disease, but as a consequence there may be more wastage (Wilson et al., 2017). With an increasing focus on waste and sustainability, and as more data are collected and models are further developed, margins of error may be reduced and potential wastage avoided. With growing research into dynamic methods of assessing micro-organisms and particularly the use of imaging methods, models will be produced that incorporate these measurements to provide more accurate predictions, or real-time measurements. Siripatrawan et al., (2011) found that they could detect E.coli using hyperspectral imaging (HI) on inoculated spinach leaves, and were able to predict the number of organisms from the imaging data using a neural network based model. Kang et al. (2011) were able to detect faecal contamination, which is a common route for pathogens to enter the food chain, using HI with romaine lettuce samples. However, there has yet to be any application of these methods and models in the retail environment.

When considering spoilage and quality, the underlying models which are used to implement a best-before date are far less developed, than those that predict use-by dates, if they are used at all. There is a lack of research into markers that can be used to reliably predict quality, creating a barrier in negotiating an extension or reduction of the date on the pack as the supplier does not have sufficient evidence to back-up their perceived notion of quality. The consequence of this is that the date on the pack often does not change when the quality, and therefore shelf-life, does.

4. Human perception of quality

Often, the first and most significant parameter a consumer uses to decide if they will purchase or throw away a salad product is their visual perception (Paakki et al., 2019). The appearance is the first stimulus the consumer is faced with and is often used as a metric for acceptance or rejection of the product (Mielby et al., 2012). Therefore, having a good understanding and testing methodology for visual aspects of a product is important.

4.1 *Visual disorders associated with leafy salads*

With leafy salads, there is a plethora of different visual disorders that can occur (Figure 3). These include russet spotting, which is induced in iceberg lettuce by exposure to ethylene in the ppm range (López-Gálvez et al., 2015), or the yellowing of leaves due to chlorophyll degradation (Koukounaras et al., 2009). There are some disorders that are associated with discolouration in leafy salads that are typically induced by mechanical damage where internal cell structures are disrupted e.g. cutting. Pinking of iceberg lettuce is one such example where cell structures are disrupted allowing the interaction of compounds and enzymes that result in colour change that would not ordinarily occur if cells remained intact. Pinking is induced by the conversion of diphenols to quinones, and then melanin precipitates which produces pink and brown hues depending on subsequent reactions that are not yet fully understood (Saltveit, 2018).

[Figure 3]

As visual quality defects are instrumental in guiding the consumer's decision process, a lot of effort has been put into measuring and quantifying these disorders, both in academia and industry (Quested and Murphy, 2014; Manzocco et al., 2017). In contrast to microbiological assessment, which will often be outsourced, visual appearance will be determined within the business. Typically, visual appearance is assessed by a sensory panel or by a more objective approach involving the analysis of the emission spectra of the product. Depending on the equipment being used, this will typically be within the visible spectrum (~380 to 740 nm). Specification standards for each product will be defined and agreed upon by the supplier and retailer, and any product failing to meet the required standard will not be sold. Visual assessment by human assessors is perhaps the most common method utilised when considering the quality of a salad product over a shelf-life period due to its relative simplicity and low cost. The advantage of this approach, other than low cost, is that it is relatively quick and, when done with larger numbers of assessors, may align with the consumer perception of the product (Lee and Chandra, 2018; Nguyen et al., 2019; Sikora et al., 2020).

5. Instrumental assessment of quality

Objective assessment of visual quality has long been the goal of laboratory scientists studying postharvest changes. Only recently are these technologies being adapted for supply chain applications and the primary point at which they are implemented are in the packhouse. Often the use of image analysis, hyperspectral imaging or colorimetry (see sections 5.1-5.3 below) are used for automating sorting materials of very different visual qualities e.g. removing senescent spinach cotyledons from consignments of dark green baby leaf spinach leaves. Only recently has the possibility emerged of using such technologies to detect color/reflectance changes at an early stage that enable the prospect of some better prediction of shelf life.

Several technologies rely on the real-time detection of volatile aroma compounds that are produced as a consequence of senescence, tissue damage, degradation or microbiological proliferation on the leaves (Luca et al., 2017). Generally, the aroma is a tertiary consideration when consumers are assessing salad leaves, since they cannot smell the product without damaging the packaging. Furthermore, unless the salad leaves are particularly pungent or have a distinctive odour, such as rocket leaves, there is not much of an aroma to detect. From a food safety perspective, the aroma is not necessarily diagnostic of pathogens but off-odours are often associated with the presence of microorganisms.

Identification of suitable volatile marker compounds has come from extensive work based on assessment by the human nose in the form of trained sensory panels or preference testing using untrained consumer panels. The human nose is, compared to current levels of technology, more sensitive than the equipment that is available for automated volatile sensing. As with visual appearance, there are several quantitative and qualitative methods for assessing aroma. Most often, a sensory panel is used to assess the aroma of a product; depending on the question being asked, a trained panel or untrained consumer panel will be used. Assessing a product using a panel can give both quantitative and subjective feedback in a real-world setting. Using a trained sensory panel to determine the descriptive characteristics of a product is common. Descriptive analysis can also be used for quality control, and often it is used to determine consumer preference (Goularte et al., 2004; Murphy et al., 2011; Wieczyńska and Cavoski, 2018). There are many different methods for profiling a product with a sensory panel, such as quantitative descriptive analysis (QDA), and free-choice profiling (Murray et al., 2001). Typically, there are 8-16 trained panel members who produce an agreed vocabulary for attributes of the product. Descriptive characteristics, with rocket as an example, may pick up on aromas such as: peppery, green, mustard, sweet (Bell et al., 2016). The attributes of the product are then scored using an interval scale. However, without also identifying and quantifying the volatile organic compounds (VOCs), it is not possible to ascertain which compounds are responsible for which aromas, but research in this space has given rise to the identification of compounds which may be used to diagnose deteriorating quality (Dryahina et al., 2020), the potential of which is discussed in 5.4 and 5.5.

Different technologies have started to impact on the fresh produce market that give a real-time indication of freshness, or historical reporting of cold chain breaches. These typically rely on detection of respiratory gases and/or use chemistry to report changes in physical parameters such as temperature or humidity. These are covered in sections 5.6 and 5.7, together with a discussion of their potential and limitations.

5.1 *Image analysis for assessing leafy salads*

Image analysis (IA) is a more objective approach to assessing visual appearance and is becoming the predominant phenotyping method. Phenotyping refers to the observed characteristics of an organism, such as morphology, colour and biochemical properties. With IA, typically an RGB image is captured using anything from relatively inexpensive consumer devices such as mobile phone cameras (Tsaftaris and Noutsos, 2009); to more advanced dedicated equipment where spectral data in single nm bandwidths can be collected for each pixel (Lara et al., 2013). Once the images have been captured, features such as colour and size of the subject can be extracted using one of the many software packages dedicated to IA.

One website alone, www.quantitative-plant.org, has links to over 170 different tools for plant phenotyping and 28 open data sets that can be used to train models (Lobet et al., 2013). With the use of machine learning algorithms for advanced feature extraction, the technology is progressing very quickly (Jiménez-Carvelo et al., 2019). IA is also much more applicable to industrial applications, as it can be automated, and is used in many different industries. Mo et al., (2017) developed a method for detecting foreign bodies on fresh-cut lettuce where a hyper-spectral scanner was placed above a moving conveyor belt. The analysis of the images captured by the camera was able to distinguish between lettuce and foreign bodies based on their absorbance in the range of (400-1000 nm), and reject samples accordingly.

The development of machine learning algorithms, that can enable leaf material to be imaged whilst still inside packaging, has been demonstrated, which is important if post-harvest monitoring is to be achieved. In the paper of Cavallo et al. (2018), a convolutional neural network (CNN) was used to segment the images into three classes: plant, packaging and other. Currently, deep learning and CNNs are the go-to method for working with image data as, once the models are trained, they can be very fast in their decision making, allowing the possibility of live processing (Patrício and Rieder, 2018). There is no reason why this approach could not be applied to other leafy salads, and even be incorporated into consumer technology, such as smart phones.

5.2 Colorimetry for assessing leafy quality

Another method of classifying colour is with the use of chroma-meters (Mampholo et al., 2016). Chroma-meters are analytical instruments for measuring colour, which is typically presented in the LAB colour space. The advantage of this method is that it can be carried out with only one assessor, and objective data are obtained. The device measures a small area on the target (~1 cm^2) and therefore, depending on the target size and variability of colour, many measurements may need to be taken to accurately capture the colour of the target. One issue with this approach, particularly when it comes to salad leaves, is that there are sometimes large differences within individual leaves and between different leaves in the same pack. As the technique measures the leaf at different points, only average values are obtained, which makes it difficult to discriminate between different manifestations of discolouration (Peiser et al., 1998). Prior to IA, this was the predominant method used; in recent years, the advantages that IA brings has meant that it has largely eclipsed the use of chroma-meters. Overall, considering the relative importance that the consumer places on the appearance of the product, there are few examples of methodologies for predicting colour change.

5.3 *Quality assessment using hyper-spectral imaging*

Looking outside the visible spectrum with hyperspectral imaging (HI), or reflectance data not detected by human vision, is currently providing more information about the state of the product. HI is much more expensive, both in the cost of equipment and the software and time needed for analysis. In comparison to spatial imaging where two-dimensional data is acquired, three-dimensional data are collected and each pixel has its own associated spectrum; the spectrum data (λ) in combination with spatial data (x, y) creates voxels in the form (x, y, λ). As different materials interact uniquely with different bands of the electromagnetic spectrum (EM), it is possible to gather data about the chemical composition of the material, which is one of the major advantages of HI (Chaudhry et al., 2018). HI has been used to differentiate between rocket leaves stored at varying temperatures, and from this to infer quality. A random forest classifier was able to classify the reflectance data obtained from the imaging and correctly identify unseen samples 79% of the time (Platias et al., 2018). Specific regions of the spectrum have been shown to be more informative than others. Diezma et al., (2013) found that 710 to 900 nm was particularly important for the degradation of spinach leaves. Simko, Jimenez-Berni and Furbank, (2015) found similar results with lettuce, with 744 nm being the most informative wavelength for determining the quality difference between fresh and decayed lettuce. This is not particularly surprising as this portion of the electromagnetic (EM) spectrum is used for the basis of the normalised difference vegetation index (NDVI). NDVI distinguishes between ‘healthy’ and ‘stressed’ plants by the difference in reflection of the near-infrared (NIR) region of the EM spectrum, and has been used for a relatively long time for this purpose (Gitelson and Merzlyak, 1996).

Typically, when one method such as HI, is used alone with no further analysis, the results tend to heavily weight chlorophyll senescence, as with NDVI, as the primary factor with respect to change (Beghi et al., 2016). The measured values for colour change in packaged salad leaves are not always linear; often there is an initial change over the first few days and then a reversal (Løkke et al., 2013). The colour change and then reversal, has been theorised to be related to the accumulation of liquid inside the pack, causing some areas to degrade to a greater extent and making the leaf appear darker. The change of colour and subsequent reversal makes classifying quality based on colour alone difficult, and the technology is not suitable for implementation in the retail or consumer part of the supply chain. The image/colour/spectral analysis described in these preceding sections does have potential for automating shelf life quality assessment that is performed by packers and consequently to provide a more consistent objective analysis than currently occurs between different assessors. However, the pack houses are assessing shelf life quality in the same time frame as the consumer, so the real gains in this area would be for methods to be developed that could predict quality loss in a particular consignment ahead of when the consumer becomes aware of it.

5.4 *Detecting and identifying volatile compounds emitted from leafy salad crops*

Challenges remain to identify compounds which are reliably associated with quality and depending on how detection is implemented, specific to the salad leaves in question. Typically, gas chromatography with mass spectrometry is the analytical method of choice, preferably using the same samples for chemical and sensory panel analysis to provide comparable results. The media used to capture the VOCs before measurement on a GC system are selected based on the compounds that are expected to be in the subject material. Solid-phase micro extraction (SPME) is a method often used for capturing volatile compounds that are emitted in the headspace of a leafy salad. A fibre coated in an adsorbent material is placed inside the headspace until an equilibrium has been reached between the fibre, the sample and the headspace. After the equilibrium has been reached the fibre is then placed in the GC system where the VOCs are desorbed and detected.

Recently, a number of researchers have focused their studies on VOCs emitted from rocket leaves. Spadafora et al. (2016) found that sulphur-containing VOCs tended to increase over shelf-life; it was noted that the increase was correlated with an increase in numbers of micro-organisms isolated from the leaves. In this case, the volatiles were extracted from the headspace of the pack and captured on Tenax traps then measured using GC-MS. Similar results have also been obtained by Bell et al., (2016) using thermal desorption with gas chromatography-time-of-flight mass spectrometry (TD-GC-TOF-MS) with a comparable extraction protocol. Typically, GC-MS methods cannot quantify the abundance of VOCs over time. This is because VOC compounds are often unknown or uncommon, meaning generating standards to quantify the absolute abundance of them are cost-prohibitive. Because of this, the appearance or disappearance of specific VOCs is often used as a marker of shelf-life (Lonchamp et al., 2009; Luca et al., 2017; Ioannidis et al., 2018). For leafy salads, it is only rocket that has had more than a couple of papers identifying compounds associated with quality. The lack of informative VOCs from other salad leaves may be due to rocket being particularly pungent or conversely the lack of VOCs emitted from other leafy salad crops. The appearance of compounds such as pentane, 2-ethylfuran and dimethyl sulphide, have been identified as markers of microbial activity (Luca et al., 2017), and have been associated with degradation of quality during storage in rocket salads (Dryahina et al., 2020). VOCs arising from cellular senescence or degradation induced by the presence of micro-organisms are hard to distinguish from each other. Therefore, it is challenging to ascribe particular compounds to microbial or cellular origin.

There are many research examples (Lonchamp et al., 2009; Spadafora et al., 2016; Raffo et al., 2018) illustrating the value of detecting volatile compounds in packaged salad that claim to be diagnostic of SL. However, it is a huge leap to move from volatile detection on sophisticated laboratory equipment to a technology that is commercially viable and implemented within industry. The challenges for this technology are currently threefold: Firstly the appropriate volatile markers need to be identified for each crop; this is perhaps the most difficult step as there are many variables, e.g., cultivar, growing environment, that influence plant metabolism and therefore the volatiles released from a plant (Bell et al., 2017). The detected volatiles also need to be reliably associated with quality degradation that would be predictive of consumer rejection of the product. Furthermore, technologies for detecting the identified VOCs need to be developed that are cost-effective commercially and can work in real-time to monitor quality.

5.5 *Electronic noses for automated odour sensing*

Gas sensor devices or ‘e-noses’ can be tuned to specific VOCs, therefore once the critical compounds concerning quality are established, devices for their detection can be built at relatively low cost. E-noses are non-specific detectors and are calibrated to detect a group of compounds rather than specific ones (Cortellino et al., 2018). ‘E-noses’ are relatively new, and the technology is developing rapidly. One of the issues with e-nose devices is that they are quite variable, both in manufacturing consistency and that they can degrade in their performance over time, depending on their environment, which has adverse effects on the quality of the data they generate. There has been much effort to develop algorithms that correct any variance relative to a master device (Yan and Zhang, 2016). The issue of consistency between devices could be a significant barrier to incorporating sensors into a retail or domestic setting. For a method to be non-destructive, the sensor must either be incorporated with the packaging, which provides many challenges, but may be successful at diagnosing quality deterioration measuring generic markers of degradation such as dimethyl sulphide. Alternatively, there needs to be an external sensor that is placed within the vicinity of the subject. However, the external sensor may detect aroma from a variety of origins, and therefore, needs to monitor specific compounds and is unlikely to work for bagged leafy salads or vegetables since volatiles will be contained within the package.

5.6 *Quality sensors within “intelligent packaging”*

Sensors have been developed that can be incorporated into the packaging of a product, and therefore allow real-time feedback about the condition of the product within (Torri et al., 2008; Fuertes et al., 2016). A recent review by Beshai et al (2020) categorised intelligent packaging sensors into four types: optical, biosensors, gas, and humidity sensors. Optical sensors rely on the techniques discussed in the sub-sections above and it remains difficult to see how these can easily be incorporated into packaging in a format that can inform the consumer, although the potential for screening at an earlier stage in the supply chain is possible by linking sensors to radio frequency identification (RFID) tags to collate information and ensure data transmission throughout a supply chain.

Attention has inevitably turned towards technologies that have potential to detect foodborne pathogens, given the seriousness of the consequences if these proliferate on food destined for human consumption. Zhang et al. (2017) have made the best progress towards developing a system with a low detection threshold, through using a Janus emulsion assay which they demonstrated would sensitively and selectively binds to *E. coli* at 10^4 cfu/mL and which could be read via a smartphone app. However, this still relies on a liquid medium and, crucially, that the bacteria come into direct contact with the sensor. These are substantial assumptions and therefore there is an attraction towards sensor technologies that monitor gaseous compounds. López-Carballo et al. (2019) developed a sensor that can be incorporated within flexible packaging, of samples containing infant milk formula, utilising the redox reaction of methylene blue to signify changes in quality. As the sensor was monitoring O_2, it would only be suitable for MAP as the bag is hermetically sealed. Carbon dioxide may be a better target for gas sensors incorporated into packaging, since its atmospheric concentration is only 0.04 % whereas in MAP it tends to be in the 4-10 % range. Borchert (2013) described an optochemical CO2 sensor which uses a phosphorescent reporter dye and a colourimetric pH indicator incorporated in plastic matrix. The sensor retained its sensitivity to CO_2 for 21 days at 4 °C and could detect concentrations accurately within a minute of exposure, reporting them using a colour change requiring simple instrumentation, with a four minute recovery time. Despite the potential offered by VOCs that are specific to particular crops or that are produced as a result of microbiological contamination, to date no monitoring or detection systems have been developed that could be incorporated into packaging. Beshai et al. (2020) review current monitors for respiratory gases and humidity, but the only ‘freshness’ monitors that use non-respiratory gases depend on the sensor being in direct contact with the food which is not the case for packed vegetables and salads.

5.7 *Time Temperature Indicators*

Maintaining an unbroken cold chain is key to preserving quality and safety of fresh produce (Cantwell and Suslow, 2002) with short breaks in cold temperature less severe than prolonged periods above the optimal temperature. Even within a single cold chain variability exists, for example depending on the proximity of a pallet to the cooling system in the lorry or the location of a crate within a pallet. Two classes of Time Temperature Indicators exist: those that are data driven and those that display a colour change based on a physio-chemical reaction.

Data loggers or labels such as RFID tags that report temperature, humidity etc have been used commercially for some time, but often as stand-alone units that have to be incorporated within the packs in a crate which then need manual recovery and interpretation. There is considerable commercial attraction to the development of time-temperature indicators that can be incorporated into packaging or crate labelling systems, especially those which offer instant visual means of interpretation rather than plugging into a computer. RFID tags do offer this possibility, but they are limited by battery life, the need to be in close proximity to the reader, and their own lifespan. Torres-Sánchez et al. (2020) report the development of a multiple non-linear regression (MNLR) model that relates the temperature to the maximum shelf life in a predictive manner, but at present this relies on the integration of sensory and physico-chemical quality attributes. The best data-driven solutions therefore remain RFID tags that can integrate multiple signals from temperature, humidity and ammonia and which are sufficiently sophisticated to interpret the relationship between these parameters (Quintero et al., 2016).

Visual indicators have a great deal of appeal commercially, particularly if they report the full history that the product has experienced through the supply chain and if they can be incorporated into the packaging. At present, chemical colour change is usually reliant on the speed of an enzymic reaction linked to a pH change, polymer state changes linked to colour change, or the growth rate of bioindicator microorganisms (Lee and Rahman, 2014). They tend to only be able to report sub-optimally high temperatures, since they all work on the principal that raised temperatures lead to a faster response of the target reaction. They are therefore unsuitable for detecting when temperatures have been lower than optimal, for example if basil has been chilled below 12 ºC. An additional practical problem is that the indicators have to be stored at low temperature before they are deployed to prevent the colour change happening before the tag has been attached to the package. However, a number of TTI products are used very successfully in a commercial setting, particularly for frozen or chilled food products. Considering that leafy salads have a relatively short SL, incorporating sensors into the packing of RTE products may not offer a reasonable return on investment, especially when considering implications the sensor may have on recyclability of the product. It remains to be seen if detection and monitoring of VOCs can provide data to the consumer that allows for real-time monitoring of the health and remaining longevity of a product that they purchase.

6. Concluding remarks

Previous technological advances within the food ecosystem, particularly with respect to imaging, have been implemented at the processing stage where cameras detect out-of-specification leaves and reject them. However, as was remarked when date labels were being introduced: distribution and storage conditions are important to the longevity of a product. There is currently no way for the retailer or consumer to update their expectations of shelf-life once the date on the pack has been set. The dates placed on the packaging, if any, are the only guide the consumer has as to the quality or safety of the product. Although some methods for non-destructively measuring quality post-harvest have been explored, none have yet to be implemented in a consumer study to measure the impact such technologies could provide with regards to reducing waste. High-end consumer refrigerators are now being produced with integrated computers and cameras that are able to monitor the contents, and give real-time feedback to the consumer by network-connected devices. However, there are currently no devices on the market offering product-specific monitoring or giving real-time feedback to the consumer regarding quality or safety, and certainly not for complex products such as leafy salads that are packaged in their current format.

The economic benefit of increasing the accuracy of SL estimations has been estimated at 55 ± 15 million pounds per day of savings, per day of increased SL from UK households for leafy salads (Lee et al., 2015). Furthermore, it is estimated that retailers would save 2720 tonnes of leafy salads from waste per day of increased shelf-life. There is a clear case for providing the consumer with more accurate information about the state of the product. However, although the technology for sensing quality and safety is progressing, there is still a long way to go in order to be able to reduce the amount of waste, whilst maintaining safety and quality.

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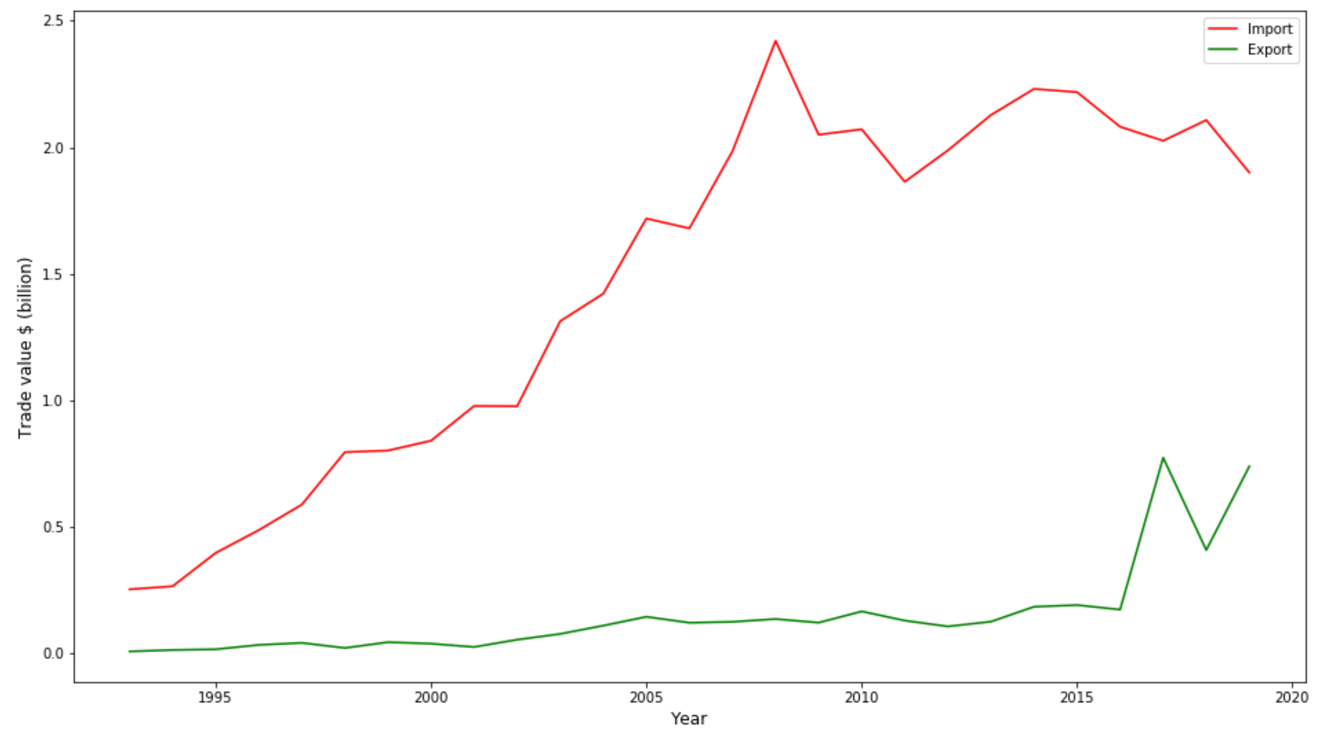

Figure 1 – The UK trade balance of leafy vegetables from the Comtrade database comprised of lettuce, spinach and chicory (https://comtrade.un.org/).

Table 2. Microbial limits of safety and quality for precut fruit and vegetables (ready-to-eat).

Pertaining to safety

Micro-organisms	Absolute limit	Testing method reference	Stage at which the legislation applies
E. coli 0157:H7[1]	1000 cfu/g	ISO 16649-1 or 2	Manufacturing process
Listeria monocytogenes[1]	Absence in 25 g	EN/ISO 11290-1	Before the food as left the food business operator
	100 cfu/g	EN/ISO 11290-2	Products on the market during its shelf-life
Salmonella[1]	Absence in 25 g	EN/ISO 6579	Products on the market during its shelf-life

Pertaining to Quality

Micro-organisms	Class A Satisfactory	Class B Acceptable	Class C Unsatisfactory
Aerobic Colony Count[2]	$< 10^4$ cfu/g	$10^4 - < 10^5$ cfu/g	$\geq 10^5$ cfu/g
Aerobic Colony Count[3,4]			$> 10^7$ cfu/g
E. coli[2]	< 20 cfu/g	$20 - < 100$ cfu/g	≥ 100 cfu/g

1. (EC 2073/2005, 2006)
2. (Food and Environmental Hygiene Department, 2001)
3. (Calonica et al., 2019)
4. (Health Protection Agency., 2009)

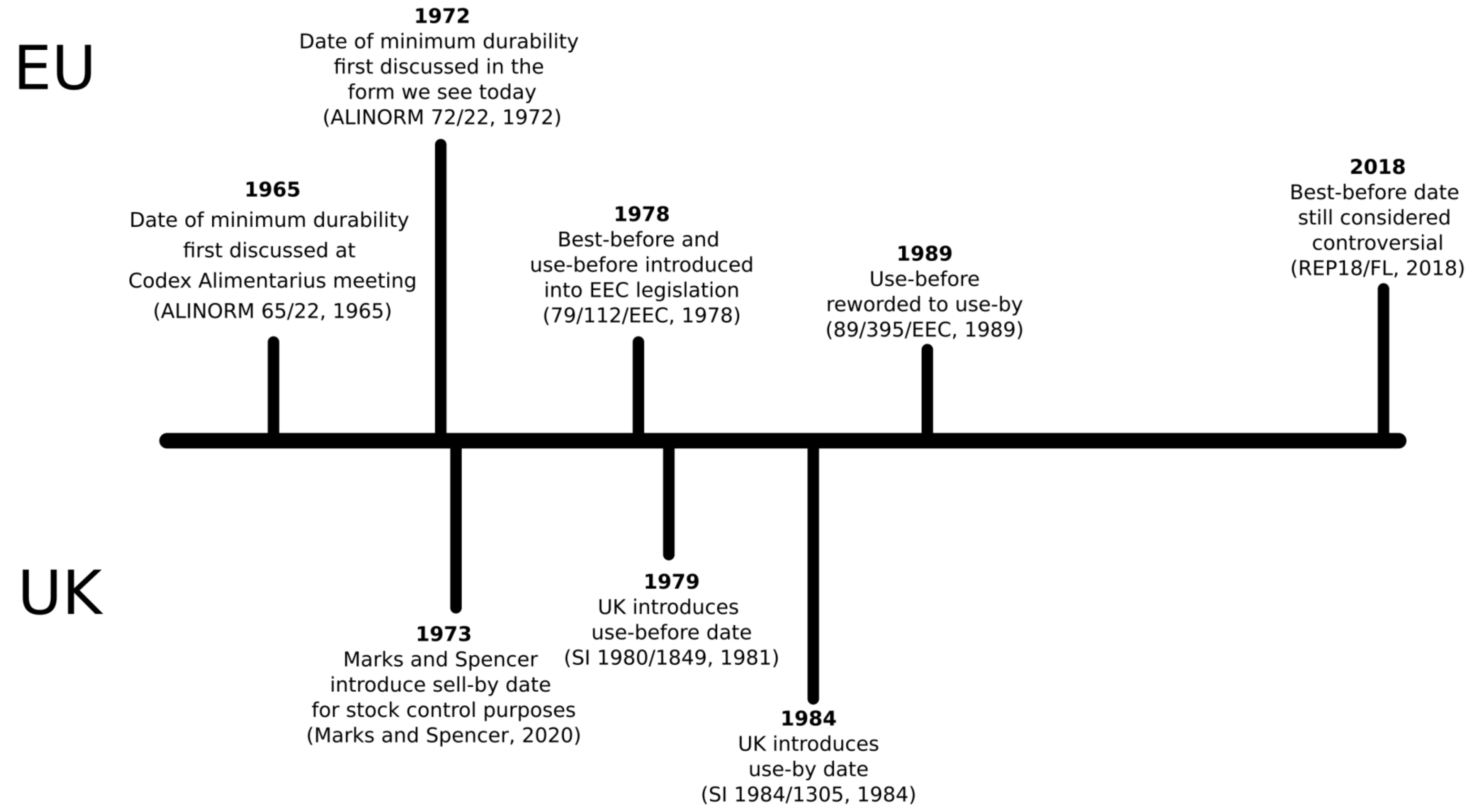

Figure 2- A timeline showing key milestones in the formation of on-pack date labeling that we see today in the UK and EU.

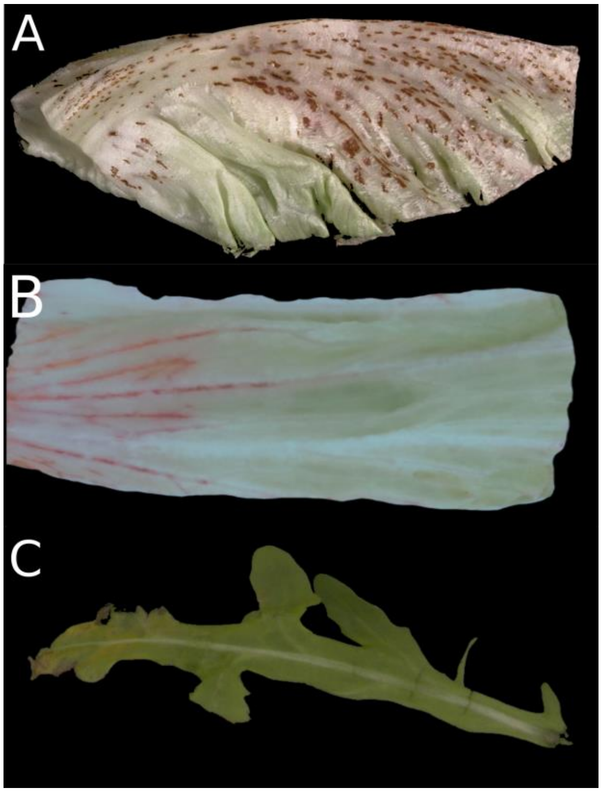

Figure 3. Example visual disorders of salad leaves. Russet spotting on Iceberg lettuce (A), Pinking of cut tissue of Iceberg lettuce (B), and senescence of Rocket leaves (C) . Image (A) was taken from (Cantwell and Suslow, 2002)