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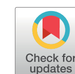
Review

Pulsed light as an emerging technology to cause disruption for food and adjacent industries – Quo vadis?



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ABSTRACT

Background: – Despite verbose amount of publications and having gained approval by Food and Drug Administration (FDA) since 1996 for food-surface disinfection applications, pulsed light (PL) still has not been used on a large scale by industry. Fresh produce remains a leading cause of foodborne illness outbreaks where there is a pressing need for an effective post-harvest decontamination intervention such as PL that can replace or supplement post-harvest washing.

Scope and approach: This review describes current status of PL for non-thermal food-surface treatments. It addresses rationale and efficacy of methods used to assess PL disinfection performance along with addressing interrelated factors that are limiting PL development for these opportunities.

Key findings and conclusions: PL is a promising non-thermal technology for food-surface disinfection. Lack of international harmonisation and consensus on what constitutes priority experimental methods and exposure conditions is hampering commercial development of PL. Previously, many studies have reported on PL-food treatments using a cumulative energy dose or range of UV doses above the FDA recommended 12 J cm^{-2}. Consensus on the choice and relevance of indirect cell and molecular methods to assess injury in PL-treated microorganisms has yet to be reached. This review provides recommendations in reporting experimental data and key parameters governing treatment that enables reporting of sufficient details to extent that other researchers would be able to repeat, compare and evaluate data between studies. Converging developments in adjacent industry sectors that may inform development of PL as a promising future food disruptive technology are described.

1. Introduction

The food sector is the largest manufacturing sector in the EU with €1,098 billion turnover employing 4.24 million people (cited Saguy, Roos, & Cohen, 2018). As our global population continues to grow, so too does the demand for the supply of more safe nutritious food (Michelini, Principato, & Iasevoli, 2018; Richie et al., 2018). This global population growth also brings added challenges including the need to diversify our food supply chain to meet changing diets including growing individualism, diet-related diseases, demand for personalised food products, the rise of 'flexitarianism' (i.e., eating predominantly, but not strictly, vegetarian), an increasing aging population, and greater ethnic or cultural influences. These are projected to bring about a 70% increase in demand for more food over the next 40 years (DBEI, 2018). There has been a commensurate rise in the growth of "Foodomics' to respond to these opportunities (Valdéz, Cifuentes, & León, 2017; Rychilk, Kanawati, & Schmitt-Kopplin, 2017) along with increased digitisation of processes and markets. In addition, future sustaining of our global food supply chain will experience added pressure due to increasing uncertainties associated with impact of global warming on crops, which includes more droughts and flooding. Climate change will also continue to influence choice of innovation with preference for developing less energy-intensive eco-friendly food processes. The aforementioned highlights a trend towards increasing complexity of our food supply chain that requires more international collaboration and harmonisation of management efforts in order to adequately deal with risks to consumers (Quested, Cook, Gorris, & Cole, 2010) including food safety (Richie et al., 2018).

Fresh-cut produce remains the leading cause of foodborne illness outbreaks (Smith DeWall & Bhuiya, 2007; Callejón et al., 2015) surpassing that of meat, dairy and seafood (CDC, 2018). Moreover, fresh food produces are frequently contaminated by a range of potentially hazardous microorganisms including complex chlorine-resistant parasites (Centres for Disease Control and Prevention, 2018; Franssen et al., 2019). Several researchers have previously reported on the open nature of the fresh produce chain where contamination may be introduced at

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several points in the production, harvesting and processing, and then passed on to consumers (Murray, Wu, Shi, Xue, & Warriner, 2017; Nuesch-Inderbinen & Stephan, 2016). Best published evidence shows that a critical post-harvest washing step conducted under commercial conditions has limited decontamination efficacy and may potentially lead to unwanted cross-contamination of produce (Gombas et al., 2017; Murray et al., 2017). Although on-farm good agricultural practices (GAP) can reduce contamination in the field and help minimise cross-contamination during post-harvesting handing (Francis et al., 2012), a more effective means to ensure the food safety of fresh produce is to apply post-harvest decontamination interventions that may complement or replace post-harvest washing (Felizani, Lichter, Smilanick, & Ippolito A, 2016; Meireles, Giaouris, & Simoes, 2016; Murray et al., 2017). Worldwide, there is an increasing consumer demand for ready-to-eat fresh-cut fruit and vegetables where this additional commercial processing step presents additional to prevent microbial cross-contamination and to main food safety (Yu, Neal, & Sirat, 2018).

Kramer, Wunderlich, and Muranyi (2017) also suggested several beneficial reasons why PL should be developed as a possible nonthermal technology for surface decontamination of produce including (a) minimally processed foods are typically consumed without additional washing or heating and they mostly display use by dates of several days allowing for growth potentially hazardous microorganisms; (b) the cold chain may not always be properly maintained; (c) plant tissue integrity may be impaired by cutting processes; (d) perishable products such as raw poultry are frequently contaminated with high numbers of pathogenic bacteria such as *Campylobacter* and *Salmonella* species; (e) many minimally processed fresh produce cannot be harshly treated; (f) heating is not applicable for meat, fish or fresh produce, and (g) alternative use of chemical biocides such as chlorine may not be preferred due to potential formation of toxic byproducts like trihalomethanes. Although physical technologies like pulsed electric fields (PEF) and high hydrostatic pressure (HHP) are quite well advanced for commercial scale deployment, these treatments may not be appropriate to meet the surface decontamination and packaging needs of industrially-fabricated ready-to-eat fresh-cut produce. Murray et al. (2017) reported that most approaches to address this food surface decontamination step for ready-to eat fresh-cut produce are typically still at laboratory scale. Increasing research on the use of pulsed light (PL) is a promising but is has yet to reach its' market potential for large scale industrial use despite gaining approval from the Food and Drug Administration (FDA) in 1996 for food surface treatments (Schottroff et al., 2018). PL seeks to achieve a balance between applying effective nonthermal treatment yet maintaining fresh-like food properties as detectable by means of changes in texture, colour, chemical composition or sensory attributes (Kramer et al., 2017; Van Impe, 2018). There are also potential consequences for food safety including evidence of the emergence of viable but not-culturable (VBNC) state microorganisms post PL treatments that may lead to an underestimation of produce microbial quality status (Rowan, Valdramidis, & Gomez-Lopez, 2015; Schottroff et al., 2018; Zhao, Zhong, Wei, Lin, & Ding, 2017).

A related consideration for large scale development of PL technology is the apparent lack of quality of harmonised data surrounding experimental methods and exposure conditions for food treatment technologies that will enable other researchers to repeat, interpret and evaluate data enabling large scale industrial deployment (Schottroff et al., 2018). This appears at odds with the development of similar or different physical treatment technologies in adjacent industries such as the water (TrojanUV, 2016; Fitzhenry, Rowan, Val de Rio, Cremillieux, & Clifford, 2019) or medical technology sectors where there is potential for knowledge transfer. However, there is a trend towards cross-cutting use of innovative technologies such as PL to meet complex food safety challenges including recalcitrant foodborne parasites (Franssen et al., 2019) and other emerging opportunities such as infant milk formulae treatment (McFadden et al., 2017) and even extrusion-based 3-D printing of proteins and fibre-rich materials (Lille, Nurmela, Nordlund, Metsä-Kortelainen, & Sozer, 2018). Therefore, this review will address challenges and opportunities influencing PL development for large scale uptake by the food industry along with providing recommendations for standardising reporting by researchers. Future potential for PL to cause technology disruption is considered.

1.1. Pulsed light as example of emerging technology

Pulsed light (PL) is a nonthermal disinfection technology that has attracted attention over the past 15 years as a promising minimal process to improve the microbial safety or to extend the shelf life of treated foods (Schottroff et al., 2018). PL has been described as a cost-effective, nonthermal technology that does not generate unwanted residuals on treated food surfaces (Hayes, Kirf, Garvey, & Rowan, 2013). PL has also been referred to as high-intensity pulsed UV light (HIPL), pulsed UV light (PUV), high-intensity broad-spectrum UV light (BSPL), intense light pulsed (ILP) and pulsed white light (PWL) (Schottroff et al., 2018). The number of published research on PL technology has substantially increased as attested by 247 citations in Google Scholar in respect of my initial study on use of this innovation for treating food-borne microorganisms (Rowan et al., 1999). PL has been approved by the FDA in the production, processing and handling of foods since 1996 up to cumulative UV dose or fluence of $12\,J\,cm^{-2}$ where emission spectra to be kept between 200 and 1100 nm and pulse duration at $\leq$ 2 ms (Food and Drug Administration, 2015). However, PL has been developed for commercial scale food packaging with little evidence of large scale food treatments. However, emerging applications include ready-to-eat, freshly-cut, fruit and vegetables along with decontamination of meat and fish products and associated packaging (Table 1). The technological principle of pulsed light disinfection is based upon the accumulation of high discharge voltage in a capacitor where the stored energy is delivered in ultra-short pulses through a light source filled with xenon gas. This xenon-light source emits a broad spectrum light flash typically in the range of ca. 200–1100 nm with approximately 25% in the UV range (Kramer et al., 2017). It is considered that PL disinfection efficiency is higher compared with continuous-wave low-pressure UV irradiation (CW-UV) due to its high peak power along with the ability to deliver its stored energy over short durations, typically 1 to 10 pulses per second. The main parameters governing effective PL operational for disinfection are the fluence [$J\,cm^{-2}$] over exposure time [s], number of pulsed applied [n], pulsed width [τ], frequency [Hz], and the peak power [W] (Hayes, Laffey, McNeil, & Rowan, 2012a; Hayes, Fogarty, Clifford, & Rowan, 2012b; Hayes, Garvey, Fogarty, Clifford, & Rowan, 2012c; Rowan et al., 2015).

1.2. Development of PL technology for large scale commercial usage in food and other areas

Given that the volume of data published on PL technology for different food surfaces and types is verbose, what are technological gaps or trends in published information that maybe limiting PL development for commercial uptake? A review of existing literature reveals that PL lacks harmonisation and standardisation of data to inform technology acceptance for the food sector for large scale uptake (Table 1). No single PL study to date has holistically addressed reliable and repeatable operation using a broad range of pathogenic and spoilage microorganisms, which demonstrates significant methodological variance where currently there is non-cohesive or consensus for standardised development of PL internationally. These observations also corroborate recent review of Schottroff et al. (2018) who commented that published research outcomes for PL treatments for different foods are incomparable as basic information on parameters is lacking such as details of lamp manufacture, geometry of target matrix and so forth. Table 1 highlights significant variation in PL operational conditions on food quality parameters and targeted microorganisms that generates an enormity of data that is lacking harmonisation and varies in rigor. This particular

Table 1
Variation in parameters measured pre and post PL-treatments of foods and beverages.

Vegetables (n = 15) & Fruit (n = 8)	Food Quality Changes Measured	PL-Operational Settings (n)	PL-mediated Microbial Reduction (CFU)	Meat & Fish Products (n = 13)	Food Quality Changes measured	PL Operational Settings (n =)	PL-mediated Microbial Reduction (CFU)
Greenbell peppers **Iceberg lettuce** **Soybean Sprouts** **Radicchio** **Carrots** **White Cabbage** (Gómez-López, Devlieghere, Bonduelle, & Devevere, 2005)	Increase in respiration rate; sensory deviation during storage (n = 2)	**No fluence reported**. 675 and 2700 pulses at 7 J for 45 and 180s. 7 °C for 9 days under MAP (n = 4)	Aerobic mesophilic count (n = 1)	**Chicken Frankfurters** (Keklik, Demirci, and Puri (2009) Ready-to-eat **Sausages** (Uesugi & Moraru, 2009) **Raw salmon fillets** (Ozer & Demirci, 2006)	Colour; lipid peroxidation (n = 2) Not determined (n = 1) Colour loss; Temperature increase to 100 °C (n = 2)	≤**0.25 cm** $^{-2}$; ≤13 cm (n = 9) **9.4 J cm** $^{-2}$; 48 days; 4 °C or combined Nisin (n = 5) **5.6 J cm** $^{-2}$; ≤60s; ≤ 8 cm (n = 8)	*L. monocytogenes* Scott A (≤1.9 log) (n = 1) *L. innocua* (1.37 log with PL; 4.03 log with Nisin + PL) (n = 1) *E. coli* O157:H7 (≤1.09 log) *L. monocytogenes* Scott A (1.2 log) (n = 2)
Mushrooms (Fresh-cut) (Oms-Oliu, Aguiló-Aguayo, Martín-Belloso, & Soliva-Fortuny, 2010)	Texture, colour, polyphenol oxidase, Vit C, heat damage high fluence (n = 5)	≤**28 J cm** ^{2} per pulses up to 60s; up to 13 cm distance; sealed PP-trays, (n = 13)	Native microflora (n = 1)	**Chicken** through plastic films (Haughton et al., 2011)	Discolouration at high treatment intensities	**No fluence reported**. 505 J per pulse; ≤30 s; 3 Hz; (n =	*E. coli* (1.69 log) *Salmonella enteritidis* ATCC 13076 (1.69 log) *Campylobacter jejuni* (1.22 log) (n = 3)
Avocado (Ramos-Villarroel, Martín-Belloso, & Soliva-Fortuny, 2011)	Colour, texture, O_2 and CO_2 increase, reduction ethylene (n = 4)	**0.4 J cm** ^{2} per pulse for 15 to 30 pulses, 5 °C dark, 15 days; PP-film/PP-trays (n = 6)	*E. coli* (2.61–2.97 log) *L. innocua* (2.9–3.33 log) (n = 2)	**Beef and Tuna Carpaccio** (Hierro, Ganan, Barroso, & Fernández, 2012)	Sensory attributes and colour parameters (n = 2)	≤**11.9 J cm** $^{-2}$; 4 °C; 28 days (n = 5)	*L. monocytogenes* Scott A ≤0.9 log *E. coli* (≤1.2 log) *S. enterica* serovar Typhimumium (≤1 log) *Vibrio parahaemolyticus* (≤1 log) (n = 4)
Green onions (Xu, Chen, & Wu, 2013)	Not determined	**5 and 14.3** J cm ^{2} (dry PL) **56.1 J cm** ^{2} (wet PL) *	*E. coli* O157:H7 > 4 log reduction	**Seafood** (shrimp, salmon, catfish) Cheigh et al. (2013)	No impact on colour; Max Temperature rise 5 °C (n = 2)	≤**17.2 J cm** $^{-2}$; ≤9800 pules; ≤1960 s (n = 12)	*L. monocytogenes* KCCM 40307 (≤2.4 log) (n = 1)
Tomatoes (Aguiló-Aguayo, Charles, Renard, Page, & Carlin, 2013)	Softening, increased weight, impact on ascorbic acid, (n = 6),	**2.68 J cm** $^{-2}$; 2.5 k/20 °C; 15 day (n = 2)	Microflora (1 log) *S. cerevisiae* (2.5 log) (n = 2)	**Pork and Salmon** (Nucorescu et al., 2014)	Dose dependent colour change in port and liquid peroxidation in salmon at high fluences (n = 3)	**3, 10 or 30 J cm** $^{-2}$ 3 cm distance from light source, 1 Hz at 4 °C [n = 3]	Aerobic plate count (< 1 log reduction)
Strawberries and **Blueberries** (Huang, Ye, Cao, and Chen (2017)	Not determined (n = 0)	≤**22.5 J cm** $^{-2}$; ≤25s; 16 cm distance (n = 5)	*E. coli* O157:H7 (≤3.8 log) *Salmonella Newport* H1275 (≤4.2log) MNV-1 (≤3.8 log) (n = 3)	**Beef/pork, chicken/turkey**, and **deer/rabit/kangaroo** (Tomašević, 2015)	Dose dependent change in sensory and colour change particularly at high fluences (n = 4)	**3.4 cm J cm** $^{-2}$ 6 and 10 cm distance from light source, 1 and 5 pulses, 3 kV (n = 4)	Not determined.
Spinach (Agüero, Jagus, Martín-Belloso, & Soliva-Fortuny, 2016)	Increase respiration, antioxidant capacity, total polyphenolic content, colour (n = 5)	≤**120 kJ cm** $^{-2}$; ≤30 pulses; 8.5 cm distance 4 °C; 10 days (n = 12) PE trays sealed with PP film	*E. coli* (≤2.3 log) *L. innocua* (≤2.6 log) Total plate count (≤2.2 log) (n = 3)	**Apple Juice** (Muñoz et al., 2012)	No impact on pH, nonenzyme browning or total antioxidant activity; colour change (n = 4)	**5.1 J cm** $^{-2}$ but 1.2 J cm $^{-2}$ per pulse under continuous flow rate – distance 1.9 cm; 17 and 13.4 ml min-1; 3 Hz; (n = 4)	*E coli* DSM 1607 (4.9 log reduction)
Mung bean sprouts **Endive Salad** (Kramer et al., 2015a, 2015b)	Colour, respiration due to UV-C content of PL (n = 2)	≤**3 J cm** $^{-2}$, 10 cm, 5 °C, 6 days, (n = 7)	*E. coli* DSM 498 (≤2.34 log) *L. innocua* DSM 20649 (≤1.55 log) Total Viable Count (≤2.46 log) (n = 3)	**Goat Milk** (Kasahara, Carrasco, & Aruilar, 2015)	Aroma changes; no impact upon viscosity, density, pH, moisture, ash (n = 6)	1.3–**10 J cm** $^{-2}$; 0.41 J cm $^{-2}$ per pulse; 20 Hz, 1–8 s; 3 ml sample in quartz cell (n = 4)	*E. coli* DHS (6 log reduction)

(*continued on next page*)

Table 1 (*continued*)

Vegetables (n = 15) & Fruit (n = 8)	Food Quality Changes Measured	PL-Operational Settings (n)	PL-mediated Microbial Reduction (CFU)	Meat & Fish Products (n = 13)	Food Quality Changes measured	PL Operational Settings (n =)	PL-mediated Microbial Reduction (CFU)
Raspberries Strawberries (Bialka & Demirci, 2008)	Weight, colour, sensory attributes (n = 4)	**≤72 J cm^{-2}**; ≤60s; ≤13 cm distance (n = 13)	*E. coli* O157:H7 (≤3.9 log) *S enterica* (2.8 ≤ log) Several outbreak strains (n = 6)	**Apple, Melon, Orange** and **Strawberry juices** (Ferrario, Alzamora, & Guerrero, 2013)	Temperature increase by up to 16.8 Oc (n = − 4)	**2.4–71.6 J cm^{-2}**; 10 cm distance; 2–60 s; 4.9 ml PL-treated in petri dish (n = 5)	*L. monocytogenes* (≤4.5 log in apple juice; ≤1 log orange juice; ≤0.3 log strawberry juice); *E. coli* (≤2 log orange juice);
Raspberries and Strawberries (Huang and Chen, 2015)	No significant discolouration (n = 1)	**≤63.2 J cm^{-2}**; ≤60s, water assisted PL alone & combined with 1% H2O2 (n = 12)	*E. coli* O157:H7 *S. entericica* (several outbreak strains) Murine norovirus (≤4.4 log) (n = 3)	**Raw Milk** (Innocente et al., 2014)	Increase by 30 °C (55 °C absolute); up to 94% inactivation of alkaline phosphatase	0.26–**26.25 J cm^{-2}**; 0.5 Hz, 1 cm distance; 3 ml sample (n = 5)	Total microbial count (≤3.2 log unit reduction)

table illustrates broad range of examples from published work on PL treatments to emphasise a trend in metadata where the reader is referred to the comprehensive reviews of Kramer et al. (2017) for a more complete set of findings. Table 1 shows that of the 141 food products tested significant variation is found in log unit reductions that may depend on *inter alia* PL-treated pathogens, level of applied fluence (0.14–580 J cm^{-2}), distance from light source (3 cm–18 cm), food storage temperature (range 3 °C to 28 °C), aerobic or atmospheric packaging, use of combinational treatment technologies such as hydrogen peroxide or preservatives. Review of published research available reveals that many do not include the FDA approved upper threshold fluence value of 12 cm^{-2} in their PL-food treatment studies (Table 1). Moreover, several PL-food treatments studies operated at either a single or range of fluences well above this FDA recommended cumulative energy dosage, yet no rationale for this appears obvious.

A recurring focus was the PL-treatment of artificially-seeded or natural food products in plastic packaging in the format of trays or films that is of commercial interest (Table 1). However, the value of latter data arising of PL-treatment of plastic packing is of limited usefulness given their negative impact on environment and commensurate drive to replace plastics with sustainable alternatives such as with compostable or recyclable material. Some studies report a max temperature rise of 5 °C after 9800 pulses over range 0–17.2 J cm^{-2} with no impact upon seafood colour along with marginal ≤2.4 log unit reductions of *L. monocytogenes* (Cheigh, Hwang, & Chung, 2013). Others describe temperature increases up to 100 °C within 60 s of PL-treatment in raw salmon fillets at 5.6 J cm^{-2} with only modest ca. 1 log CFU reductions in *E. coli* O157:H7 and *L. monocytogenes* Scott A (Ozer & Demirci, 2006), which is surprising given that PL is considered to be a non-thermal process. There appears to be inter-parameter investigation of the contributing role of each factor in terms of statistical significance of disinfection outcome. Evidence-based research from published literature has demonstrated potential for PL to inactivate a range of pathogens on different food types and surfaces along with limited treatments in beverages (Table 1). However, consensus on standardised methods and equipment used that would inform process validation is holding back development of PL technology as there is lack of sufficient data for garnering industrial confidence.

If one delves deeper into published studies many additional factors are described that influence PL treatment of food products (Table 1). Again, there is no one specific study that addresses a broad set of parameters across representative microorganisms of food safety and spoilage interest (Table 2). The focus of previous publications was to apply varying levels of PL treatments to destroy pathogens and to reduce or eliminate spoilage microorganisms under conditions that have minimal impact on nutritional or organoleptic properties for extended shelf life. The overwhelming operational factor governing PL-mediated disinfection is the measured UV dose or fluence (J cm^{-2}) and all future studies should report on findings using this parameter as a measure to move towards international harmonisation. As only 25% of the broad spectrum intense light pulses are in UV range that decreases in efficacy with increased distance from light source to target surface, it is important to standardise and define distances used for food treatments. Currently, distances over the range 3 cm–18 cm from light source to target surface have been reporting in the literature (Table 1). Notwithstanding variances in microbial species and strains reported post PL-treatments, a trend has emerged exhibiting deceasing resistance to PL irradiation roughly in the order fungal spores, bacterial endospores > parasites > viruses > and > vegetative bacteria. Our previous research has demonstrated that pigmentation protects fungal spores against the action of PL as these pigments absorb light optimally in the UV-C region that may be attributed to an evolutionary adaptive trait (Anderson, Rowan, MacGregor, Fouracre, & Farish, 2000). Few studies have focused on complex pathogens such as foodborne parasites or viruses, due to the need for developing alternative and sophisticated in vitro bioassays such as combined RT-qPCR with mammalian cell

Table 2
Variation in the number and types of microorganisms and approach used during PL-treatments of natural and artificially-contaminated fruit and vegetables, meat and fish and beverages.
* Source data, Kramer et al. (2017); -, not tested.

Microorganism or Enumeration Method Applied	Number of food products treated with PL where test microorganism studied*			
	Fruit and Vegetable (n = 80)	Meat and Fish Products (n = 24)	Beverages (n = 37)	Total Food Products (n = 141)
Aerobic Mesophilic Count	19 (23.75%)	1 (4.2%)	2 (5.4%)	22 (15.7%)
E. coli O157:H7	6 (2.5%)	2 (8.3%)	1 (2.7%)	9 (6.4%)
E. coli (non VTEC)	9 (11.25%)	2 (8.3%)	12 (32.4%)	23 (16.4%)
Salmonella enterica	4 (5%)	4 (16.6%)	3 (8.1%)	11 (7.8%)
Microflora	2 (2.5%)	–	1 (2.7%)	3 (2.1%)
Alicyclobacillus acidoterrestris	–	–	1 (2.7%)	1 (0.7%)
Listeria innocua	10 (12.5%)	1 (4.2%)	6 (16.2%)	17 (12.2%)
Listeria monocytogenes	2 (2.5%)	7 (29.1%)	–	9 (6.4%)
Aerobic & Facultative Anaerobic Heterotrophs	–	–	1 (2.7%)	1 (0.7%)
Saccharyomyces cerevisiae	2 (2.5%)	–	4 (10.8%)	6 (4.2%)
Penicillium expansum	–	–	1 (2.7%)	1 (0.7%)
Yeasts and Moulds	10 (12.5%)	–	–	10 (7%)
Bacillus cereus	1 (1.25%)	1 (4.2%)	1 (2.7%)	3 (2.1%)
Pseudomonas aeruginosa	–	–	1 (2.7%)	1 (0.7%)
Total Viable Count	3 (3.75%)	1 (4.2%)	–	4 (2.8%)
Lactobacillus brevis	1 (1.25%)	–	–	1 (0.7%)
Salmonella Newport	4 (5%)	–	–	4 (2.8%)
Murine Norovirus MNV1	2 (2.5%)	–	1 (2.7%)	3 (2.1%)
Total Plate Count	5 (6.25%)	–	–	5 (3.6%)
Salmonella Typhimurium	–	2 (8.3%)	–	2 (1.4%
Campylobacter jejuni	–	1 (4.2%)	–	1 (0.7%)
Vibrio parahaemolyticus	–	1 (4.2%)	–	1 (0.7%)
Clostridium perfringens	–	–	1 (2.7%)	1 (0.7%)
Pseudomonas fluorescence	–	1 (4.2%)	–	1 (0.7%)
Cryptosporidium parvum	–	–	–	1 (0.7%)

culture that also encompasses gold standard mice infectivity studies (Garvey, Farrell, Cormican, & Rowan, 2010). Consequently, several related studies have involved microorganisms such as bacterial endospores as putative surrogates of similar or greater resistance kinetic profiles for the aforementioned parasites that adds to complexity and appropriateness of data (Hayes et al., 2012a, 2012b, 2012c; Garvey et al., 2014a, 2014b). Table 1 further highlights the enormity of data to be considered in terms of ready-to-eat and freshly cut fruit and vegetables (n = 80), meat and fish products (n = 24) and associated PL-impact on quality determinants (n = 37). There appears no standardised approach to investigating or comparing microbial reductions using PL-technology with *E. coli* studied the most as represented by 32 of 141 samples (24.8%), followed by *Listeria innocua* (17/141, 12.2%) as surrogate to the pathogen *Listeria monocytogenes* that was studied in 9 out of 141 food products (6.4%) (Table 2). There is also significant variance in the choice or selection of test organism per food group that makes comparisons between studies on microbial death rate and disinfection efficacy incomparable. This highlights that lack of consensus on an agreed list of test species and strains (such as using a specific ATCC, NCIMB or NCTC reference strain of *E. coli* along with potential inclusion of a recalcitrant endospore as surrogate organism such as a member of the *Bacillus* genus) among international scientific community in order to compare efficacy and understand PL processing. Standardising method for fluence determination is also highly relevant given reported variances from μJ to J cm^{-2}, such as using recent dosimetry method of Gómez-López and Bolton (2016) along with developments in biodosimetry in water industry (TrojanUV, 2016). Moreover, food processors progressing with industrial scale development of PL must also consider 5 log-pathogen reduction performance standard required by the HACCP regulation (Food and Drug Administration, 2003). This 5-log reduction must be targeted to the 'pertinent pathogen', which is the most resistant microorganism of public health concern that may occur in food. For example, the pertinent pathogen may vary with the type of treatment of product such as typically *Salmonella* or *Escherichia coli* O157:H7 for juices. PL as designated control measure can be considered for reduction in the pertinent microorganism by at least 5-log or can be used in combination of control measures that have a cumulative effect of a 5-log reduction and must be accomplished within a single production facility operating under CGMP's. Currently, there appears to be a lack of consideration for the 5-log pathogen reduction performance standard rule in published domain which may relate in part to the inability of PL to achieve a maximum viable count reduction beyond 4 log orders of artificially-inoculated test microorganisms or native microflora on PL-treated food surfaces using xenon light sources and existing equipment configurations (Tables 1 and 2).

There has been an increasing interest in the development of PL technology for surface decontamination of fresh produce given that this as a leading source of foodborne illness (Centres for Disease Control and Prevention, 2018) along with the commensurate worldwide interest in developing an appropriate intervention that would enable effective commercial food-surface decontamination post-harvest handling and packaging (Table 1) including interest in extended shelf-life. It was previously but incorrectly assumed that the post-harvest wash step was sufficient to remove field-acquired contamination with much of the research performed focussed on efficacy of sanitizers (Feliziani et al., 2016; Murray et al., 2018). The impact of PL on the quality attributes of treated fresh produce encompassing fruit and vegetables, meat and fish, and beverages is variable and were typically determined by evaluating changes in texture, colour, chemical composition or sensory attributes (Kramer et al., 2017) (Table 1). Many studies previously reported that increasing fluence intensities negatively influenced several quality parameters in fresh fruit and vegetables including colour of salad (Kramer, Wunderlich, & Muranyi, 2015a, 2015b) or sensory attributes of cut apples (Ignat, Manzocco, Maifreni, Bartolomeoli, & Nicoli, 2014) (Table 1). Kramer et al. (2017) recommended performing specific storage microbial trials under real conditions to include testing quality parameters as significant deterioration is mostly not found immediately post PL exposure, but during storage. PL treatment of plant based fresh produce has also been attributed with formation of health-promoting and nutritive compounds such as carotenoids, lycopene and total phenolic compounds of PL-treated green tomatoes (Pataro et al., 2015) or increased concentrations of phytochemicals in mangoes (Lopes et al., (2016) (Table 1). Kramer et al. (2017) reviewed quality changes in PL-treated meat or fresh fish and noted occurrence of lipid oxidation along with sensory deviations but cannot dismiss the influence of potential overheating from intense PL treatments of the product surface (also presented in Table 1). There have been fewer studies published on the potential impact of PL-treatment on quality attributes of beverages (Table 1). However, mainly changes in colour in PL-treated apple juice or sensory deviations were observed particularly at higher fluence (Kramer et al., 2017). However, pathogen reduction is highly variable due to uneven food surfaces or cavities in surface microstructure that can protect or harbour untreated microorganisms due to shading effects (Murray et al., 2018). For example, pathogen inactivation on cantaloupes and berries is typically restricted to 1 log CFU with fluence of 12 kJ m^{-2} (Adhikari, Syamaladevi, Killinger, & Sablani, 2015) using conventional UV-C light source.

Future sustainability surrounding the development of PL treatment of fresh produce is likely to entail use of different light sources such as LEDs (Kim, Kim, & Kang, 2017) along with using different configuration in treatment chambers design that deliver pulsed light at multiple

Table 3
Factors affecting PL-disinfection performance.

PL- Operational parameters	Microbial and Environmental Parameters	Methods of microbial enumeration, resuscitation and PL-treatment evaluation	Cell and molecular mechanistic factors governing PL-killing
Number of applied light pulses (Elmnasser et al., 2007; Kramer et al., 2017; Bhavya & Umesh-Bebbar, 2017; Van Impe, 2018)	Sequence from high to low-PL resistance. Fungi [Levy, Aubert, Lacour, & Carlin, 2012; Huang et al., 2018]; bacterial spore (Levy et al., 2012); yeasts (Farrell et al., 2011); protozoan parasites (Garvey et al., 2010; Hayes et al., 2012a, 2012b, 2012c); viruses (Huang et al., 2017; Vimont et al., 2015) and vegetative bacteria (Wang, MacGregor, Anderson, & Woolsey, 2005)	Direct viable count (Rowan et al., 2015) Use of selective dyes (Pataro et al., 2011), Antibiotics in lab media (agar and broths) (Farrell, Garvey, Cormican, Laffey, & Rowan, 2010; Rowan et al., 1999) Enrichment and resuscitation (Fitzhenry et al., 2018] Most Probable Number and end-point determinations (McFadden et al., 2017)	Cell Wall Damage using bioassays in *C. albicans* (Farrell et al., 2011) TEM in *L. monocytogenes* Cheigh et al., 2013 and SEM in *S. aureus* Kristnamurthy, Tewari, Irudayaraj, & Demirci, 2010
Applied discharge voltage (Hayes et al., 2012a, 2012b, 2012c; Kramer et al., 2015a, 2015b)	Variation in PL-resistance between microbial genus, species and strains tested (Rowan et al., 2015) along with culture forms (Bradley, Laffey, McNeil, & Rowan, 2012)	Gene expression post PL-treatments using *L. monocytognes* via Whole Genome DNA Microarray Analysis (Uesagi et al., 2016); Expression of *Nox* genes in *Trichophyton rubrum* by 402 nm-PL (Huang et al., 2018)	Cell membrane damage and rupture in *E. coli, S. aureus, B. subtilis, C. albicans* (Farrell et al., 2011; Garvey, Stocca, & Rowan, 2016; Nicorescu et al., 2013; Takeshita et al., 2003; Xu & Wu, 2016).
Distance between target and flash lamp (Rowan et al., 2015, Schottroff et al., 2018)	Population present (homogenous, mixed) (Rowan, 2004)	Flow cytometry to measure cell membrane damage *in L. monocytogenes* [Kramer & Muranyi, 2014]	Lipid peroxidation in *C. albicans* [Farrell et al., 2011]
Spectral range of light flashes – efficacy at 270 nm (Wang et al., 2005); 225–280 nm (Levy et al., 2012); no effect in visible or near infrared (Ramos-Villarroel, Aron-Maftei, Martin-Belloso, & Soliva-Fortuny, 2012)	Environmental parameters such as temperature, osmotic stress (Bradley et al., 2012; Kramer et al., 2017) and illumination conditions bib_Lasagabaster_and_de_Maranon_2014(Lasagabaster and de Maranon (2014)	Confocal and fluorescent microscopy [Nicorescu et al., 2013]	Loss of intracellular constituents including proteins [Farrell et al., 2011; [Cheigh, Park, Chung, Shin, & Park, 2012; Garvey et al., 2016a)
Number of light sources (Rowan et al., 1999)	Presence of organic matter, particle size and turbidity (liquid) negatively impacts upon efficacy (Garvey et al., 2014)	Photoreactivation and repair and length of exposure to daylight or darkness [MacLean et al., 2008; Lasagabaster; de Marañ̃ứ;n (2014); Fitzhenry et al., 2018)]	UVC- induced DNA damage [Rastogi, Richa, Tyagi, & Sinha, 2010; Farrell et al., 2011] Ramos-Villarroel et al. (2017))
Method of measuring fluence or UV dose (J cm^{-2}) (Hsu et al., 2011; -López and Bolton, 2016)	Older cultured of bacteria less PL-sensitive (Cudemos, Izquier, Medina-Martines, & Gomez-Lopez, 2013; Farrell, Garvey, & Rowan, 2009)	Combined qPCR and cell culture (for complex parasites and viruses) [Garvey et al., 2010; Garvey, Coughlan, Murphy, & Rowan, 2016b]	Indirect damage to cellular components such as proteins or lipids by ROS using fluorescent probes, RT-qPCR, micromorphology and MTT assay (Farrell et al., 2011; Huang et al., 2018; Massier et al., 2013, 2012)
Agar (Aguirre et al., 2015) versus food PL-treatments Kramer et al. (2017)	Gram stain reaction (bacteria) (Rowan et al., 2004)	Modelling of kinetic data such as single, bi and tri-phasic plots [Aguirre et al., 2015; Rowan et al., 2015] Modelling of pulsed light penetration and matrix colour (Aguirre, Herro, Fernandez, & de Fernando, 2014]	Necrosis and apoptosis in *C. albicans* [Farrell et al., 2011]
Statistical power of trials and runs (Rowan et al., 2015)	Planktonic or biofilm (Garvey et al., 2015, ; Montgomery & Banerjee, 2015)	PL-exposed unculturable bacteria expression of proteins in *S. enterica* via synthesis of plasmid-encoded GFP (Kramer et al., 2017)	Loss of esterase activity in *Saccharomyces cerevisiae* (Ferrario et al., 2014)
Liquid treatments including beverages and water (Fitzhenry et al., 2018)	Exposure to prior stress, tempering, sublethal injury (Wutack et al., 2003) generation of VBNC state bacteria (Rowan et al., 2015; Schottroff et al., 2018)	Measurement of ATP [Garvey et al., 2010] Measurement of PL-induced oxidative stress response via proteomic studies (Massier et al., 2012, 2013)	Pigmentation in *P. aeruginosa* [Farrell et al., 2010]. Pigmentation in *A. niger* (Esbelin, Mallea, Ram, & Carlin, 2013). Lipid Peroxidation in *C. albicans* (Farrell et al., 2011)

(*continued on next page*)

Table 3 (*continued*)

PL- Operational parameters	Microbial and Environmental Parameters	Methods of microbial enumeration, resuscitation and PL-treatment evaluation	Cell and molecular mechanistic factors governing PL-killing
Applied frequency of pulses in the range 1–5 Hz (Luksiene, Gedelis, Buchovec, & Raudeliuniene, 2007)	Combination treatments (thermosonication, PEF), PPGD and VBNC phenomenon (Kramer et al., 2015a,b, 2017; Kramer & Muranyi, 2014)	Scanning Electron Microscopy (Huang et al., 2018; Nicorescu et al., 2013) and Transmission Electron Microscopy [Cheigh et al., 2012; Cheigh et al., 2013; Ferrario et al., 2014; Huang et al., 2018]	Possibly over-heating of intracellular fluid (Xu & Wu, 2016)

*Abbreviations – Pulsed Electric Fields (PEF); Pulsed Plasma Gas Discharge (PPGD), Viable but Not Culturable State (VBNC); Green fluorescent Protein (GFP); Real-time quantitative polymerase chain reaction (RT-qPCR); Transmission Electron Microscopy (TEM); Scanning Electron Microscopy (SEM); Reactive Oxygen Species (ROS).

angles to overcome shaded areas (Chen, Loeb, & Kim, 2017). Murray et al. (2018) suggested that additional advantages of using LEDs are the potential to use a range of different wavelengths such as UV-C thereby providing a possible synergistic antimicrobial actions. This approach may be particularly applicable for inactivating complex foodborne parasites where other wavelengths in the pulsed spectrum may also contribute by destroying important cellular macromolecules and structures (Garvey et al., 2010; Rowan et al., 2015). This alternative approach to using Xenon light sources may also help alleviate a tailing' effect that is often observed in PL-mediated microbial dose-response curves due to sub-populations surviving treatment or those harbouring in surface cavities due to protective shading effects, which infers that inactivation is limited to a certain microbial log-reduction threshold irrespective if increased fluence intensity is applied (Rowan et al., 2015). Consideration must also be given to effectiveness of smart packaging for PL food treatments, which was the subject of a recent review by Heinrich et al. (2016) with some informative studies highlighted in Table 1. Effectiveness of existing packaging for food surface decontamination using PL depends upon the type of polymer or combinations thereof employed where use of polypropylene or low-density polyethylene appear suitable as a high proportions of UV-C are transmitted (Kramer et al., 2017). However, data generated from current research using PL should consider that future food packaging is likely to comprise alternative biodegradable materials that are either recyclable or compostable and will replace non-environmental friendly plastics.

Consensus on agreed methods will enable meaningful evaluation between different reported PL-treatments possible and will provide baseline-data suitable for actual and predictive modelling, such as deployment of three-parameter Gaussian model to describe the spatial distribution of total and UV fluence in air and also in liquid substrates (Hsu & Moraru, 2011). Gaining consensus on how to analyse or model metadata generated from emerging technologies such as PL will be informed by advances in data analytics and machine learning (Moral, Hinde, & Demétrio, 2017). Considerable future focus can then be given to comprehensively investigating importance of kinetic inactivation data plots and relevance of single, bi and/or tri-phasic survivor responses during treatments and relevance to food industry (Rowan et al., 2015). Use of freely-available, open-access published data along with exploiting advances in data science and statistics will lead to new approaches for analysing and interpreting large or big-data from new processes that includes identifying key characteristics of observed variables and experimental/sampling designs (Pertea, Kin, Pertea, Leek, & Salzberg, 2016). This will allow for identification of new or extended models and development of new algorithms for global harmonisation of processes. This may inform future digitisation of appropriate metadata for machine interface learning and automation of processes (Keighrey, Flynn, Murray, & Murray, 2017). For example, there are several non-linear inactivation kinetic models that do not consider non-standard random effects that can also be addressed by using mathematics and statistical modelling such as re-parameterising datasets along with use of specific probability distributions. What is also lacking in published domains is goodness-to-fit of the statistical models for fitting data. New models will help researchers better understand the potential significance of the occurrence of shoulder and tailing phases on kinetic plots arising from PL treatments that considers factors that influence efficacy of decontamination performance post-harvest of produce (Moral et al., 2017). The power of harmonised inter-laboratory interdisciplinary modelling is exemplified by a Dutch research consortium BaSyC that has recently taken on the challenge of building a synthetic biological cell at a project cost of €25 m (Dogertom, 2018). BaySyC consortium recognises that 'A fundamental understanding of life within a cell will bring huge intellectual, scientific and technological rewards', and it is envisaged that gaining a holistic understanding of molecular machinery in cells will inform efficacy of adjacent needs such as control measures.

1.3. What lessons can be gleaned for PL studies conducted at the cell and molecular response level?

In order to advance PL as a food treatment process, there has been a concerted effort to gain an improved understanding of cellular and molecular mechanistic responses in PL-treated foodborne microorganisms, which has also contributed to the enormity of data generated (Table 3). Growth in the number and variety of sophisticated culture and enumeration methods used has been driven in part by observations of significant variances between populations of PL-treated CFU survivors enumerated on conventional laboratory based media and to that of elevated number of test microorganisms exhibiting cellular vitality (Rowan et al., 2015). These differences in microbial survivors become more apparent when applying low or moderate fluence that represents less severe surface processing conditions (Table 3), which has been attributed to the occurrence of viable but non-culturable state (VBNC) in PL treated bacteria. Less stressful operational conditions generally promote photoreactivation effects in several PL-treated microorganisms. The aforementioned has resulted in under-appreciation in the levels of bacterial survivors by as much as 4 log orders in conventional viable count or CFU enumerations (Kramer & Muranyi, 2014). This variance leads to uncertainty in PL-treatment performance that presents significant challenges to the food industry in terms of harmonisation of processes internationally. But what value do complex mechanistic cell and molecular studies offer and is there too much emphasis placed upon these? The ultimate underpinning purpose of their pursuit is to define reliable and repeatable PL-conditions that leads to irreversible destruction of targeted pathogens and reduction of spoilage microorganisms balanced with retention of fresh-like qualities. There lies the conundrum, when is irreversible destruction achieved in PL-treated foods achieved when one considers typical contamination levels? Table 3 highlights current published methods that measures cell and molecular damage in a variety of food-borne and medical-related micro-organisms that are very diverse in design and applicability. There

has been no consensus internationally on what constitutes efficacy for each measurement approach along with use of universal control for validation.

Studies performed thus far to elucidate cellular response of bacteria to PL demonstrates irreparable modifications of treated DNA molecules as a main source for inactivation (Table 3). Kramer & Muranyi, 2014 reported a relationship between onset of PL-induced count reduction in *L. innocua* and occurrence of DNA alterations. However, there is evidence supporting other detrimental damage to macromolecules and cellular structures such as cell membrane or cell wall that are exacerbated with increasing fluence causing irreversible lethal effects (Table 3). However, comparison of details underpinning methods reveals that findings are mostly incomparable due in part to lack of harmonisation of applied fluences reported for various PL systems along with limited information on geometry and configuration of equipment. The rupture of microbial cells after PL treatments is mostly attributed to a combination of photochemical and photophysical effects, resulting in short overheating of microbial cells or the pulsing effect (Kramer et al., 2017). Irreversible rupture of cell member by PL-treatments also brings about loss of vital cellular constituents such as proteins as reported in *C. albicans* (Farrell, Hayes, Laffey, & Rowan, 2011) and *S. cerevisiae* (Ferrario, Guerrero, & Alzamora, 2014). Commensurate indirect cell damage of cellular components such as proteins and lipids also occurs due to formation of reactive oxygen species in PL-treated *E. coli* (Kramer et al., 2015a, 2015b) and *C. albicans* (Farrell et al., 2011). However, a concerted future study employing whole genome sequencing (WGS), bioinformatics and real-time determinations of these cellular responses (such as using flow cytometry combined with magnetic cell sorting) may help elucidate time points associated with occurrence of single and combined cellular effects underpinning sublethal and lethal injury in PL-treated micro-organisms. Selection of markers will be critical to inform automated flow cytometry studies and these panels can eventually be incorporated into MALDI-TOF for international standardisation of processes at cellular level (Fario, Tavanti, Barnini, Ghelardi, & Lupetti, 2018). However, Uesugi, Hsu, Worobo, and Moraru (2016) previously investigated the response of *L. monocytogenes* to PL on the basis of a whole genome DNA microarray analysis, but did not find any distinct differences in gene expression after exposure to PL. While the authors concluded that microbial effects of PL mainly seem to be attributable to UV content, there is increasing evidence to suggest that other cellular damage occurs at higher fluence levels in various PL-treated micro-organisms (Table 3). An understanding of cellular and molecular damage may potentially demarcate occurrence of lethality in PL-treated microorganisms and help unravel significance (if any) of viable but not culturable state (VBNC) in bacteria (Rowan et al., 2015). There has been no data available which shows that VBNC bacteria pose a risk to human health (Kramer et al., 2015a, 2015b).

To date, there has been no published inter-laboratory study that holistically investigated PL treatments in a broad range of foodborne microorganisms that also encompasses a range of cellular responses (Table 3). Farrell et al. (2011) determined occurrence of sequential and combined cell and molecular damage in medically relevant yeast in a single study. The authors reported that increasing fluence levels resulted in PL-mediated lethality through a multi-hit cellular process that did support emphasis on UV-C destruction of genetic material. However, it also demonstrated step wise damage in other PL-treated macromolecules and cellular structures that roughly coincided with the sequence lipid hydroperoxidation of cell membrane, ROS generation, DNA damage, onset of necrosis and apoptosis, rupture of the cell membrane with loss of vital cell constitutes to the environment, and ultimately microbial death. Occurrence of onset of late necrosis and early-phase apoptosis also coincided with total absence of growth in of PL-treated yeast in laboratory media and may possibly constitute a future biomarker for informing real-time indirect lethality in this organism (Table 3).

Future mechanistic cellular information underpinning efficacy of PL-disinfection technology may be informed by whole genome sequencing (WGS) and next-generation sequencing (NGS) that includes high-throughput sequencing of mRNA (RNA-seq) of treated microbial samples post PL-treatments (Mortazavi, Williams, McCue, Schaeffer, & Wold, 2008). Such real-time investigations will benefit from recognising the added value of exploiting shared data from open access and source publishing, open methodology, open data management, open education, open licensing (Angers-Loustau et al., 2018). RNA-seq experiments generates very large, complex data sets that demand fast, accurate and flexible software to reduce the raw data to comprehensive results (Mortazavi et al., 2008). Pertea et al. (2016) describe use of free, open-source software tools, namely HISAT (hierarchical indexing for spiced alignment of transcripts), StringTie and Ballgown for comprehensive analysis of RNA-sequence experiments. This allows scientists to align reads to a genome, assemble transcripts, including novel splice variants, compute the abundance of these transcripts in each sample and compare experiments to identify differently expressed genes and transcripts. Pertea et al. (2016) describes protocol for all steps necessary to process large set of raw sequencing reads and create lists of gene transcripts, expression levels, and differently expressed genes and transcripts that typically takes 45 min of computer time. RNA-seq experiments capture the total mRNA from a collection of treated cells and then sequence that RNA in order to determine which genes were active, or expressed, in those cells. Using high-throughput sequencing machines, a single experiment can capture the expression levels of thousands of genes at once with high efficiency. There experiments generate enormous numbers of raw sequence reads, typically number in the tens of millions, even for a modest sized assay. The number of reads produced from each gene can be used to measure gene abundance that can also easily detect genes and gene variants that are not included in standard annotation, including noncoding RNA genes.

It is envisaged that exploiting whole and next generation sequencing (Ronholm, 2018; Rosen, Friedrich, & Moran-Gilad, 2018) and bioinformatics (Marco-Ramell et al., 2018; Angers-Loustau et al., 2018) may unravel relevance of suite of priority parameters governing PL performance that includes main molecular drivers that are involved in adaptive responses to PL exposure under lethal and sub-lethal conditions. The development of adjacent innovation in automated flow-cytometry (Brascli et al., 2018; Léonard, Bouarab Chibane, Ouled Bouhedda, Degraeve, & Oulahal, 2016) and spectrophotometric analysis (such as high resolution mass spectrometric methods) will also inform PL treatment efficacy under minimal processing conditions. Thus, given advancement in ICT, simple adoption of this bioinformatics protocol can be applied to inform and unravelling complex challenges in microbiology, parasitology and virology from comforts of your own home your personal notepad or computer. For example, cross-cutting research between molecular biologist and ICT are conducted frequently by researchers in our laboratories, which includes ease for remote data analysis by researcher using portable personal computers. Yoon et al. (2017) described how improvements in the quality of WGS for international sharing where bioinformatics tools can then be used to inform processes. These authors introduce an integrated database, called EzBioCloud (www.ezbiocloud.net/), that holds the taxonomic hierarch of bacterial and Archaea, which is presented by quality-controlled 16S rRNA gene and genome sequences. Hino et al. described benefits of 18S rDNA Illumina sequencing for non-culturable species such as parasites where state-of-the-art is predominantly relient upon microscopy and staining technique in fields of ecology, evolutionary biology and epidemiology. Method is easy and quick compared to conventional methods that can be applied to assess biodiversity of parasites in host alimentary tract and allows use of NGS to perform assessment in high-throughput manner. The aforementioned highlights the applicability of new molecular tools for potentially informing PL-technology development for high-throughput processing and validation.

Collectively, the aforementioned studies have produced an enormity of complex 'big data' sets for evaluation and interpretation by food technologies. But, how best to consider relevance, value and impact of

Table 4
PL used for different applications in various domains that potentially demonstrates second order technology disruption.

Application	Description	References
Cosmetic skin treatment	PL used for hair removal, photo rejuvenation (such as treatment of skin pigmentation, sun damage and thread veins) and acne	Barakat, Moftah, El Khayyat, and Abdelhakim (2017)
Optometry and ophthalmology	PL treatment of evaporative dry eye disease due to meibomain gland dysfunction. PL-treatment of keratoconus. PL-treatment of rosacea-associated meibomain gland.	Toyos, McGill, and Briscoe (2015) Seo, Kang, Ha, Chin, and Jung (2018)
Sequelae of breast cancer treatment	Chronic radiodermatitis is common sequelae of breast cancer – PL treated telangiectasia after radiotherapy	Nymann, Hedelund, and Hædersdal (2009)
Treatment of skin cancer	IPL used for photodynamic therapy in treatment of nonmelanoma skin cancer	Piccolo and Kostaki (2018)
Tissue engineering, regenerative medicine, additive manufacturing	Pulsed light for tissue engineered cartilage	Ishihara, Sato, Ishihara, Mochida, & Kikachi, 2007; Ifkovits & Burdick, 2007
Electronics	PL permits a scalable nanotechnology process for treatment of metal nanowire (NW) fusion to increase network activity. PL-sintering of nanoparticles into thin films used in transistors, switches, electronic devices. PL-sintering of CH3NH3Pbl3 solar cells.	Kang, Sowade, & Baumann, 2014; Lavery et al., 2016; Shankar, Salcedo, Berndt, & Choi, 2017; Dexter, Gao, Bansal, Chang, and Malhotra (2018).
Food packaging	PL-treatment of food packaging materials	Heinrich et al. (2016)
Food surfaces and beverages	PL-surface treatment of fresh-cut and whole vegetables, soft fruits, meat and fish	Kramer et al. (2017)
Wastewater treatment	Treatment of wastewater including complex murine noroviruses	Vimont et al. (2015)
Pollination Industry	PL-treatment of pollen to remove complex parasites affecting bumblebees	Naughton, Tiedeken, Garvey, Stout, and Rowan (2017)
Dairy water reprocessing	PL treatment of dairy wastewater for reprocessing	Fitzhenry et al. (2018)
Algal toxins and potentially bloom	PL-treatment and reduction in algal toxin okadiac acid to freshwater crustacean *Daphnia pulex*	Murray et al. (2018)
Freshwater aquaculture	PL-treatment of pond water for reduction of microbial and algal communities	www.morefish.ie (accessed 14/11/2018)

this for commercial uptake of PL? Future-proofing of PL will benefit *inter-alia* from international consensus on key operational parameters that governs effectiveness including (a) full description of equipment and dosimetry underpinning reporting of fluence; (b) agreement on standardise list of test microorganisms for all PL studies to support continuity and inter-study comparisons; (c) agreement on use of appropriate kinetic model to assess efficacy of PL-disinfection performance; and (d) freely-available open access data sources; and (e) specific engagements with industry to produce sufficient quality data to validate process. A more comprehensive suite of recommendations for future reporting of experimental data and exposure conditions for PL treatments is presented in Table 5, which also considers parameters for commercial food treatments. This guidance will enable reporting of sufficient details to extent that other researchers would be able to repeat, compare and evaluate data between studies.

1.4. What lessons can be learned from adjacent medical device sector by way of standardisation and harmonisation of data for commercial deployment of PL technology/

PL and other non-thermal technologies achieve disinfection, which is destruction of pathogens that also leads to reduction in numbers of spoilage microorganisms. These minimal processing approaches apply less severe stresses so as to consider retention of freshly properties with minimal impact on food quality characteristics along with the need for ensuring bioburden reduction for safety considerations (Rowan et al., 2015). Minimal processing technologies are markedly different to commercial sterilisation processes, such as use of gamma, x-ray and electron beam irradiation, and ethylene oxide gas for medical technology (Medtech) industries where it is generally accepted that the latter sterilisation methods are designed to over-process a specific biological indicator (either *Geobacillus stearothermophilus* or *Bacillus atrophaceus*) to ensure log 6 killing that provides sterility assurance to the welfare of the patient (Sella, Vandenberghe, & Soccol, 2015). These biological indicators (BIs) have been included in all terminal sterilisation processes for medical device as the inactivation of such highly-resistant BIs are more resistant to commonly occurring healthcare-associated pathogens and this process follows agreed international sterilisation standards where there is consensus on efficacy (Steris AST, 2018). This concept is in part similar to use of surrogate *Bacillus* endospores (such as *B. megaterium* or *B. subtilis*) described earlier as means of indirectly determining efficacy for PL-treatment of complex parasites where latter is shown or reported to be of lesser resistance to easily cultured endospores (Hayes et al., 2012a, 2012b, 2012c). It is estimated that the Medtech sector demands a market of some $350-400Bn (DBEI, 2108), where sterilised devices have a long history of not contributing to hospital acquired infections. There is also oversight from an International Standards Organisation Technical Committee. It is appreciated that processing technologies including PL for surface decontamination do not need to achieve sterilisation efficacy, and lessons to be gleaned from this adjacent sterilisation domain are of consensus on agreed standards internationally with harmonisation of methods through rigorous validation system (Mendes, Brandão, & Silva, 2007). Recent published evidence suggests that there are emerging opportunities for 3-D printing of heat-sensitive food-derived biologics for adjacent healthcare applicants that will necessitate reduced processing conditions, which may be met by use of pulsed light (Lille et al., 2018).

1.5. Harmonisation and standardisation of data – regulatory and life cycle assessment considerations for PL development

Castro et al. (2018) advocated that there should be governing bodies to regulate and monitor the enforcement of food-processing regulations and to avoid situations where it becomes challenging to interpret relevance of regulations that often only apply to countries belonging to specific organisations. There is also an emerging trend to exploit advances in life cycle analysis (LCA) in order to ascertain impact of traditional and novel food treatment technologies that can extend to highlight future assessment of PL in terms of energy consumption, carbon footprint and environmental impact (Finnegan et al., 2018; Fitzhenry, Rowan, Finnegan, Zhan, & Clifford, 2018; Pardo & Zufia, 2012). This LCA approach can be used to develop and assess more efficient and sustainable food products throughout their whole life cycle including PL surface treatment provision. Future development and exploitation of PL for food surface decontamination should also consider potential impact on the environment including carbon footprint and energy consumption where this information is currently lacking. Additional examples of exploiting LCA to elucidate environmental impact on sustainable technologies include milk powder and butter manufacture (Finnegan, Goggins, Clifford, & Xinmin, 2017), wastewater treatment (McNamara et al., 2016) and aquaculture that includes pulsed light provisions (Tahar et al., 2018; Morefish, 2018). The

Table 5
Recommended information to be reported in studies on microbial inactivation by PL for harmonisation of research and for scalable industry needs.

Microorganism, recovery and enumeration method	Genus, species and strain of microorganism
	*Provide appropriate culture collection reference number and/or include type strain for test microorganism(s) in studies
	*Include *Escherichia coli*, *Listeria innocua* and *Bacillus cereus* endospore along with native microflora for food treatments
	*Confirmation of identify of test microorganisms by biochemical, physiological, morphological, immunological and/or molecular means (provide name of supplier for rapid test kits)
	*Method of storing cultures (cryoprotectant) and frequency of sub-culturing (using fresh microbial slope every month kept at 4 °C)
	Initial inoculum
	● Description of procedures for microbial cultivation including name of supplier company for media
	● Growth medium composition, growth temperature, pH, incubation time, and growth phase (exponential or stationary)
	● Growth achieved under static or orbital cultivation (rpm)
	● Confirm purity by identifying 3 randomly selected isolates
	Recovery conditions and enumeration methods
	● Composition of media used for recovery to include basal media or physiological saline as diluent
	● Time and storage conditions between treatment and microbiological analysis
	● Description of procedure for enumerating microorganisms
PL equipment	For commercial: description of power unit used for generating pulses to include equipment name of the supplier company and model
	For prototype: adequate description of components including treatment chamber, electrical configurations and specifications
	Auxiliary devices –
	⁎ Temperature probe
	⁎ Thermophile power detector and software for total broad-spectrum dose received by sample
	⁎ Transmissivity sensor to monitor %UV transmittance
PL process parameters	How fluence (J cm^{-2}) over exposure time (*t*) is calculated/measured
	● Recommended use of dosimetry method by Gómez-López and Bolton (2016)
	Number of pulses applied (*n*)
	Applied voltage (*V*)
	Frequency of pulsing (Hertz [*Hz*])
	Pulsed width (τ)
	Peak power (*W*)
	Distance of target area from pulsed light source
	Report absence of heating particularly operating at higher fluence that may contribute to microbial inactivation performance
	Absorbed 'UV dose' should be lower than calculated power output
	Specify if UV dose measured relates to full broad-spectrum energy or part thereof such as filtered at 230 nm
	Description of microbiological indicators or biodosimetry for assessing fluence measurements
	Consider photoreactivation affects especially when using low PL energy doses and wavelengths between 360 and 380 nm
	Consider reflectance and roughness of target surfaces that may reduce microbial disinfection during PL
	Consider influence of improved effectiveness of PL using photosentisers such as titanium dioxide
PL treatment medium properties and conditions	Ensure microbial population density is ≤ 7-log orders to mitigate against influence of protective shading effects
	Include 5-log pathogen reduction performance standard - however maximum inactivation of ≤3 log for viable counts is typically achieved where complete microbial inactivation is atypical for PL
	Include description of media composition, pH, aw
	Composition of menstruum used as diluent for treated samples
	Sufficient number of treatment trials and replications to provide statistical confidence of findings at 95% level; description of statistic test and version of software package (such as Minitab or SPSS)
	Description of method used to generate Bacillus endospores (natural aged for 7 days or incorporation of manganese sulphate to expedite conversion of vegetative cells to spores on agar surfaces)
	Include native microflora along with artificially seeded test microorganisms due to variability in resistance profile to PL
	Consider occurrence of cavities in plant surface microstructures that may protect microorganisms from incident light due to shading
	Consider occurrence of residual microorganisms on produce surface that may support outgrowth and affect shelf life
Food raw material	Origins, variety, maturation and storage conditions of raw materials such as plant matrices
	Plant matrices description to include variety, geographical origin, degree of ripeness, moisture content and storage conditions (temperature, humidity and storage time)
Food quality changes measured post PL treatment	Colour loss or change
	Lipid peroxidation
	Total antioxidant activity
	Sensory attributes such as flavour, aroma and organoleptic properties
	pH, density, viscosity, moisture, ash and vitamins
	Enzyme browning or loss of activity such as alkaline phosphatase
	Choice of single or multilayer films are suitable for PL treatment in package foods (some material permits transmittance of UV-C)
	Perform specific microbial storage trials under real conditions
For beverage or drink treatments including water	Static or continuous (flow rate)
	UV transmittance of test material
	Light source positioned over beverage/water with distance to target (cm) or submerged
	UV intensity field (light source output and absence of fouling)
	Composition of inorganic, organic and total suspended solids in beverages and water to include particle size

aforementioned also reflects growing awareness of carbon footprint ranking of food encompassing need for reducing greenhouse gas emissions, preserving the environmental and addressing global warming (Food's Carbon Footprint, 2018). Therefore, future sustainable studies should also consider residual energy after food treatments, including when using and optimising PL for commercial applications.

1.6. Embracing increasing sustaining and disruptive technologies – where does PL potentially reside?

There has been an increasing trend to elucidate innovation that will lead to technology disruption for greater impact, competitiveness and value to businesses (Lauer & D'Agostino, 2013; Yongfu et al., 2017;

Geels, 2018; Li, Porter, & Suominen, 2018; Sousa & Rocha, 2018). This also aligns with the ambitions of many developed countries to sustain growth through innovation for their industries such as Ireland's Food Wise, 2025 Strategy that seeks to achieve 85% increase in food exports to €19 billion, 70% increase in value added to €13 billion, 65% increase in primary production to €10 billion and the creation of 23,000 additional jobs all along the supply chain from producer level to high end value added product development (Food Wise, 2025). Bower and Christensen (1995) initially defined disruptive technologies (DTs), which essentially addressed commercial disruptions in an existing marketplace, where a new product or service (a technology) is introduced into that market. DTs were subsequently redefined by these authors (Christensen, Anthony, & Roth, 2004) and expanded by others (Govindarajan & Kopalle, 2006) to include both high-end and low-end disruptions (Schuelke-Leech, 2018). DT can be referred to as earthquake, game breaking, whirlwind, emergent technologies and are typically those that cause upheaval in the existing market structured and dominant firms by being cheaper, simpler, more convenient and effective than the existing technology (Christensen, 1997; Christensen & Bower, 1996; Schuelke-Leech, 2018).

At the opposite end of the continuum are technologies classified as sustaining technologies (ST) that offer incremental improvements over technologies already in existence. A major distinction between the two forms of technology is that as one moves along the continuum from a sustaining to a disruptive classification. However, few technologies are ever classified as disruptive; as most newly introduced technologies are of sustaining (Garrison, 2009; Schuelke-Leech, 2018). Research demonstrates that disruptive technologies have different key success factors that ST, therefore issues will arise in senior management in terms of variability and uncertainty in their evaluation and adoption of these technologies based on their prior level of familiarity, openness and experience in assessing merits of technologies. Downfall of organisations could be tracked back to poor decision-making with respect towards DT adoption. DTs will have a transformative impact on the way we consider food science and technology and indeed in the future. New innovations and applications arise supporting the delivery and exploitation of new technology-based solutions (Osiyevskyy & Dwwald, 2015). DT are by their nature nascent and only can be revealed as being disruptive in hindsight and therefore provide major problem for technological forecaster or road-mapper as require a degree of insight not required for sustaining technology (albeit still high tech) that follow the established technology product paradigm in a given industry. DT confers regime changes such as new product platform, which is far different from what the market would have experienced with ‘only’ incremental innovation. Definitions of DT focus on firm-based product technology factors; industry wide-product technology factors and gap between substitutable technological learning curves on cost and performance basis. combination of these. Customers have accepted products and services that have been enable by DT. Schuelke-Leech (2018) described that many of these have been smaller products (may require advances in micro and nanotechnologies), lighter products (advances in material technologies); cheaper products (advances in component technologies and associated manufacturing processes), more flexibility and convenient products (advanced in human factors research, ergonomics, AI), higher unit performance products (advances in chemistry, physics, materials, design, micro and nano-technology manufacturing processes), operationally simple products (may require advances in AI, robotics, and design).

Developing increasing sustaining and disruptive technologies in the agri-food domain are core to underpinning ambitious innovation-driven economies as these create value, problem solve and increase quality of life in dynamically changing global environments. Schuelke-Leech (2018) postulated a conceptual model for understanding the orders of magnitude of disruptive technologies (DT) that are potentially disruptive to business, government and to society. The author looked at these DT at two different levels. The first order disruption is a localised change within a market or industry, which accepts Christensen's conceptualisation or DT, but is not limited by it. An example of first order DT would be use of RT-qPCR for detecting complex parasites and viral pathogens in food produce (Franssen et al., 2018) or use of gas chromatography for detecting low-level chemical contaminants (Tiedeken, Tahar, McHugh, & Rowan, 2017). A first-order DT can come from a start-up, new-entrant to a market, or an existing industry. A second order disruption has much larger and broader influences, affecting many institutions and substantially changing societal norms and institutions (Schuelke-Leech, 2018). Previous definitions of disruptive technologies have focused on disruptions to commercial markets and existing firms, which Schuelke-Leech (2018) stated are on the first order of disruption (Adner, 2002; Christensen, 1997; Danneels, 2004; Dedhayir, Okelainen, & Saju, 2014; King & Baatartogtokh, 2015). Schuelke-Leech (2018) stated that second order disruptions are technological disruptions, where the impacts permeate through society. Understanding and modelling potential disruptions is merited and will require taking a holistic perspective of the socio-technical innovation ecosystems. Future trends in the interpretation of big data from convergence of cross-cutting domains will prove important as to comprehensively evaluate impact of big data from arising from emerging innovations will be challenging. Schuelke-Leech (2018) acknowledged that new innovations that progress to DT designation based upon historical evaluation of individual technologies and how these interacted with other technologies and with other technologies and socio-economic and political factors to produce disruptions. Arguably, many now established innovations would not have been viewed initially as disruptive, such as discoveries in ICT, and it only once the larger societal impacts of a technological disruption is actually known will these be proven. Thus, development of ICT and commensurate modelling of big data will be important for evaluation of DT impact that includes achieving a holistic cross-system understanding of value that embraces convergence of expertise across diversified fields of research and enterprise. Published studies have revealed that there is a trend for development of pulsed light for different applications in food and drink, healthcare, electronics, freshwater aquaculture, pollination and ecosystem services management, and environmental decontamination (such as potential mitigation of algal bloom) that would infer potential for second order technology disruption (Table 4). However, this potential for technology disruption will only be apparent in time with feedback from consumers and other stakeholders post large scale uptake by industry that may also exploit different business models.

1.7. Development of pulsed light for novel applications in pollination industry as an example of possible technology disruption for tackling complex diseases in managed bees

Animal pollinators such as honey bees, bumble bees and solitary bees pollinate our crops and wildflowers, and thus are essential for human wellbeing (Ollerton, Winfree, & Tarrant, 2011). Eighty-seven out of the main 124 crops used directly for human consumption require or benefit from animal pollination: annually, pollinator services contribute €153 billion and €54 million to the global and Irish economies respectively (Gallai, Salles, Settele, & Vaissiere, 2009). However, in Europe, and around the globe, bees face many threats and are often in decline as a result (European Commission Pollinators Initiative, 2018). This is a multi-factorial challenge as bees are predominantly impacted by stresses associated loss of habitat, starvation and diseases (European Commission Pollinators Initiative, 2018) that is a global problem. Parasites and pathogens are not new to wild pollinators as they are naturally exposed to native parasites and pathogens, but strong exposure to non-native species in combination with other pressures like poor nutrition, pesticides and other pollutants can make them more susceptible to this threat. PoshBee (2018) is an example of a pan-European H2020 platform to assess exposure hazard of chemicals, their mixtures, and co-occurrence with pathogens and nutritional stress for

solitary, bumble, and honey bees across two major cropping systems. However, what is underappreciated to the layperson is the complexity presented parasites (including mites), fungi and viruses that affect bees where there is still is no effective intervention or mitigation strategy to address this decline or spread of diseases (Vanbergen and Insect Pollinators Initiative, 2013; Goulson & Hughes, 2015). While such projects will yield important baseline ecological information along with intimating potential add-on complications exacerbated by climate change, these studies have yet to identify a suite of appropriate and affordable solutions to address these problems. The host range, natural geographic range and virulence in different bee hosts are poorly understood for bee parasites that reflects in part the absence of effective mitigation strategies to address this significant problem. It is also of considerable concern that the anthropogenic movement of managed bees for crop pollination purposes has led to the accidental introduction of bee parasites to countries and continents where they do not naturally occur, exposing native bees to parasites which may have little resistance (Goulson & Hughes, 2015). Parasites can move between managed or commercial colonies, and can even spill over into conspecific wild bee populations that is a serious concern. Such disease associations have already occurred between managed ad wild bees, both in the UK (Fürst, McMahon, Osborne, Paxton, & Brown, 2014; Graystock, Goulson, & Hughes, 2014) and Ireland (Murray, Coffey, Kehoe, & Horgan, 2013). Moreover, 73.5% of screened commercial bumble bee colonies imported to Ireland were infected with a least on harmful parasite (Murray et al., 2013). Mitigation measures that reduce parasite loads among managed bees must therefore be developed and implemented in order to protect wild bee populations.

Currently, a critical hazard analysis critical control point (HACCP) approach to identifying key pressure points has revealed potential entry points for new diagnostic, therapeutic and disease mitigation measures for pollinators (Fig. 1). For example, is appreciated that routine parasite screening of commercial, managed and wild bees can help inform extent and scope of challenge for mitigation (Goulson & Hughes, 2015). Co-occurrences of stresses associated with agrochemicals on nutrition and disease in bees can be accurately evaluated, which will include from exploiting advances in whole genome sequencing, bioinformatics and molecular techniques (RT-qPCR) along with flow cytometry (Braschi et al., 2018) will lead to new biomarkers for informing health of bees post exposures. Moreover, although some parasites can be screened using microscopy (Murray et al., 2013), molecular screening via RT-qPCR is the only way to reliably detect all bee parasites at all stages of infection (Goulson & Hughes, 2015). Reliable detection of parasites can only be carried out via destructive screening of bees and it is appreciated that individual steps to alleviate this problem, such as disinfection or sterilize of equipment and honey bee pollen are therefore essential in slowing parasite spread via managed bees (Naughton et al., 2018). Given that there is no current effective cure for any bee parasites (Goulson & Hughes, 2015), the next best option is to employ disinfection technologies to limit disease spread yet it is a sophisticated issue to assess as there is also no in vitro bioassay to pilot studies for mitigation. However, Naughton et al. (2018) conducted pilot studies that showed pulsed light effectively destroys the trypanosome parasite *Crithidia bombi* that affects bumble bees. Use of combined RT-qPCR and cell culture for assessing fluence levels the surrogate enteroparasite *Cryptosporidium parvum* was deployed to inform putative fluence level for the traposome parasite *C. bombi*. Microscopy studies revealed for the first time that PL successfully inactivated *C. bombi* compared to untreated controls, where bumble bees were fed PL-treated samples pre and post-PL treatment. It was also revealed the death in PL-treated *C. bombi* is not always instantaneous due to observations that some samples retained motility, which may be attributed to the possible multi-hit biocidal effect of broad spectrum pulsed light on both parasite DNA and cellular structures. An entry level strategy for PL usage would be non-thermal treatment of pollen that is used for feeding farmed bumble bees (Fig. 1). Recent studies with the use of gamma irradiation for pollen also shows promise in terms of killing complex honey and bumble bee pathogens, namely fungal pathogen *Ascosphaera apis*, the microsporidian *Nosema ceranae* and three honey bee viruses (Deformed wing virus [DWV], Black queen cell virus [BQCV], and Chronic bee paralysis virus [CBPV]) (Simone-Finstrom, Aronstein, Goblirsch, Rinkevich, & de Guzmann, 2018). However, the impact of gamma irradiation on nutritional composition is not yet known. Also PL may also be considered as biocide-free contact surface approach for environmental decontamination. Fig. 1 also highlights other trends in innovation possibly attributed to immunomodulation of bees through fortification of feed and coating of equipment with antimicrobial bioactives that can be subject to non-thermal processes to reduce or eliminate bioburden, such as

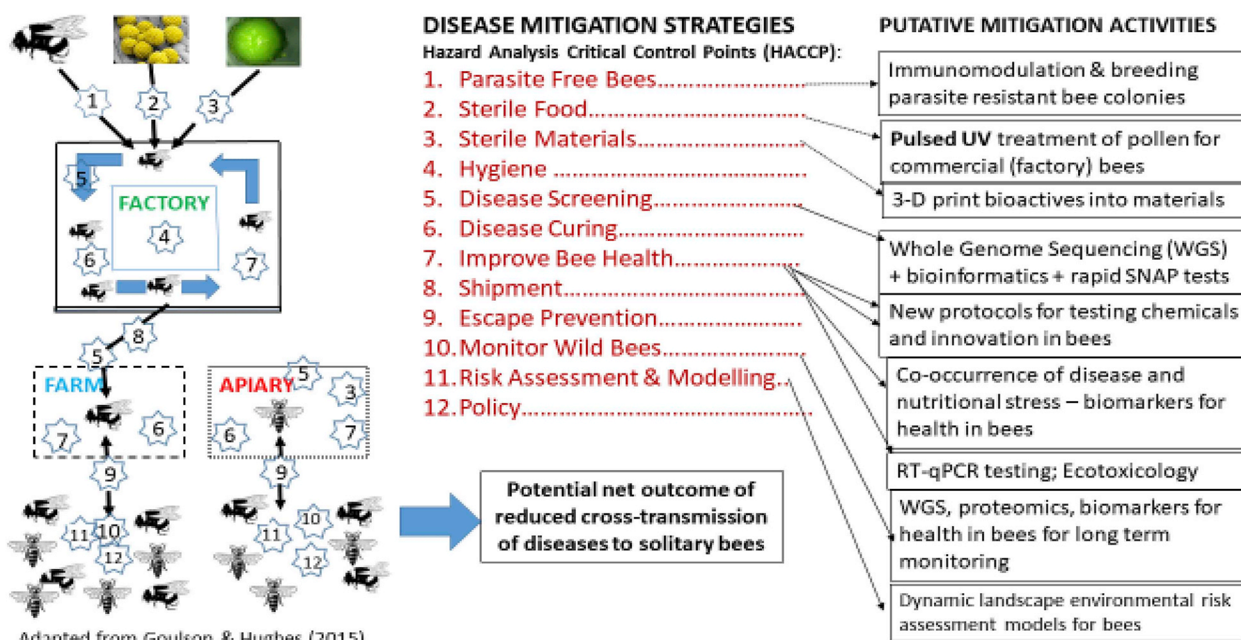

Fig. 1. Putative disease mitigation strategies and activities for promoting bee health and wellbeing that includes use of pulsed UV (PL) for nonthermal pollen treatment and contact surface disinfection.

using PL treatments. Other potential HACCP for mitigation problem may be PL treatment of wax comb that harbours parasites and viruses and is reused from year to year and transferred across beekeeping operations. Few, if any, universal treatments exist for latter control point.

1.8. Potential cross-cutting developments gleaned from the water and waste water industry where PL may lead to technology disruption

There is a commercial niche to consider development of PL as a bolt-on treatment technology for recycled water including dairy rainwater reharvesting applications (Fitzhenry et al., 2018). However, submerged flow-through PL-treatment of water presents challenges due in part to (a) relatively modest UV (25%) efficiency in PL-pulsed spectrum and (b) negative impact on other environmental factors such as presence of inorganic, organic and total suspended solids that influences UV transmittance on PL-performance (Fitzhenry et al., 2019). Conventional low-pressure emits continuously UV with 70% energy efficiency of conversion and has a long history of established success when performing at 40 mJ cm^{-2} that most regulatory bodies specify as required UV dose (TrojanUV, 2016). The potential of PL for water applications can be advanced by knowledge transfer from industry that has a history of testing and developing conventional low-pressure UV systems that includes reactor design, flow rate, UV transmittance of water, UV intensity field within reactor (light source output and fouling) and microbial inactivation for standardised validated processes (TrojanUV, 2016). PL offers additional advantages to the water industry as it produces broad-spectrum biocidal pulse that is effective against chlorine-resistant waterborne enteroparsites *Cryptosporidium parvum* (Garvey et al., 2010) or *Giardia lamblia* (Garvey et al., 2014). Therefore, there is merit in considering standalone or co-deployment of both PL and LPUV for drinking water decontamination (Garvey & Rowan, 2015). There are also other future potential PL applications that includes bespoke bolt-on treatment of contaminated seafood in depuration tanks (Vimont, Fliss, & Jean, 2015). Other contributory factors including extreme weather events (drought and flooding) associated with climate change will also support development of PL as a sustainable technology for water treatments. However, PL process requires validation before water and other industries consider large scale deploying of the technology and there are potential technical issues to be addressed in terms of re-configuring PL for optimised submerged water treatments (Fitzhenry et al., 2019).

Lessons can be gleaned from meeting challenges of detecting, monitoring and mitigating against occurrence of priority and emerging micropollutants or contaminants of concern in receiving waters in terms of embracing innovation, technology validation and commensurate need to balance or negated negative impact on environment, health and wellbeing. This also needs to an enormity of data, notwithstanding additional drivers including need to consider ecotoxicology and uncertainties of climate change. For example, in the Republic of Ireland alone there are ca 1500 waste and drinking water treatment facilities along with several hundred private water supplies that vary in efficacy of innovations for treatments, where use of low pressure UV for end-of-pipe solutions is a preferred treatment option (Tiedeken et al., 2017). What can be gleaned from the water industry for PL –technology development is the trend towards future de-risking and development of risk assessment models to simulate and predict appropriateness of innovation from evidence-based big data analysis given technological and financial constraints. There is a trend for corrective action through exploiting international cooperation of stakeholders including promoting and funding inter-laboratory testing and validation of new approaches based upon review of all data sets that also informs consensus. Such trends can be seen by development of semi-quantitative risk assessment models that considers main factors governing efficacy for mitigating pollutants in water that may also help with understanding and interpretation of enormous data sets generated from PL and other non-thermal technology studies (Tahar, Tiedeken, Cummins, Clifford, & Rowan, 2017). This also helps in simplifying complex issues and for conveying main impactful findings to industry and for policy makers for decision making. Akin to the medical technology domain, the Irish water industry require validation of new innovation before deployment that explains in part why this industry will continue to deploy validated process such as continuous-wave low-pressure UV that has been reliable for the industry. However, PL technology has potential for next-generation UV disinfection technology but requires a platform for independent validation. The latter is attested by growing interest in the use of PL for rainwater harvesting and recirculation in the dairy industry (Fitzhenry et al., 2018) and for aquaculture applications where there is a pressing need for disease mitigation using environmentally-friendly innovation that can be deployed in pond, flow-through and recirculation aquaculture systems (RAS) (cited in Tahar, Kennedy, Fitzgerald, Clifford, & Rowan, 2018a). There is an increasing trend to develop risk assessment models in order to evaluate sustainable technologies for addressing environmental treats for the drinking and wastewater industry where pulsed light can be considered as a candidate control measure post validation (Tahar et al., 2017, 2018b).

2. Conclusions

This review reflects upon some of the key technological developments underpinning PL technology where the food industry is constantly innovating and seeking more rapid, cheaper, efficient and effective outcomes. It specifically focused on the factors influencing the development of PL for the decontamination of fresh produce post-harvest handling. It also provided a set of recommendations for reporting PL studies that will facilitate standardisation and harmonisation of experimental data and exposure conditions that will enable the researcher to repeat and evaluate studies with a commercial orientation. Despite approval from the Food and Drug Administration (FDA) since 1996, there is little evidence that PL technology has not been taken up for large scale commercial treatment of foods. There has been a considerable volume of exciting published information on PL development for food and beverage applications, but there has been a marked lack of collaborative research to yield harmonised data internationally that infers PL technologies currently lead to incomparable findings. Lack of international consensus and harmonisation of data and methods will retard development of PL technology. This infers a pressing need for international networking of academics, industry, regulators and other NGOs, standards bodies such as through EU Cost Action or similar interdisciplinary inter-laboratory platform approach for testing and validating PL internationally. Such collaborative undertakings should exploit freely-available open access sources and the international research community must reach consensus on priority parameters for reliable and repeatable development of PL that recognises FDA recommendations (FDA, 2015). Decisive parameters for describing PL treatment of fresh produce to standardise future research reporting is provided that also considers the importance of including native microflora along with artificially seeded microbial test strains for specific shelf life testing at fluence levels below FDA recommended 12 J cm^{-2}. There is verbose data available on PL treatment conditions from various food produce studies, typically operating at sub-lethal level that eliminates pathogens but retains a population of spoilage microorganisms to reflect co-retention of fresh-like nutritional and organoleptic properties. However, as use of current Xenon-based light sources in current treatment configurations produce a maximum viable count reduction of 3 log orders on food surfaces, there is a pressing need to consider new light sources such as LEDs and different reactor designs to augment effectiveness of fluence to achieve the 5 log reduction standard. Advances in whole genome sequencing, bioinformatics, flow cytometry and spectrometry will help elucidate cell and molecular mechanisms underpinning PL disinfection efficacy that may bring our researcher community closer to understanding dynamic relationship between culturable and VBNC state microorganisms. This may help to inform

effective irreversible PL-decontamination processes for food produce and possible enable extension of shelf life. Agreement upon and advancing microbial inactivation (or kinetic) modelling along with developing possible risk assessment models will also inform efficacy of operational PL parameters and enable comparisons on effectiveness between studies. There is convergence of knowledge and innovation from other adjacent sectors (including medical technologies, wastewater and manufacturing industries) that will facilitate development of PL for food and related disinfection applications. However, there is an increasing trend where such sectors (such as medtech) are also investigating reduction in over-processing conditions associated with terminal sterilisation in order to embrace emerging opportunities for additive manufacturing such as 3-D printing of heat sensitive polymers and treatment of complex medical devices *in situ* in healthcare that responds to growth in personal medicine (Garmulewicz, Holweg, Veldhuis, & Yang, 2018). PL offers exiting opportunities for food and drink including potential for technology disruption in many other areas including freshwater aquaculture, waste reduction and management (rainwater recycling), pollination as putative innovation for tackling disease in bees and treatment of algal bloom. However, such potential will not be realised until agreement has been reached on harmonised methods so as to enable the research to sufficiently compare and validate data. This review also presented an opportunity to consider how PL can be used as a testbed platform for important training, education and evaluation. For example, adjacent advances in artificial intelligence, immersive augmented and virtual reality may transform how workforce training is provided and assessed including development of PL through machine interface learning (Keighrey et al., 2017).

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