Comprehensive REVIEWS in Food Science and Food Safety

The Use and Performance of Household Refrigerators: A Review

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Abstract: The domestic refrigerator is now a common household device with very few households in the developed world not possessing 1, or more, for the storage of chilled foods. Domestic storage is the last, and in many respects the most important, link in the food chill chain. Inadequate domestic refrigeration or cooling is frequently cited as a factor in incidents of food poisoning. The authors reviewed the temperature performance of refrigerators in 2008. This new review builds on that review, covering studies that have been published since (and those that were unfortunately missed in the first review), and also seeks to put this important stage of the food cold chain in its context. It is clear from the published data that many refrigerators throughout the world are running at higher than recommended temperatures. It is also clear that, despite improvements in energy use, the temperature performance and use of refrigerators have not changed significantly in the last 40 or so years. Many householders still remain unaware of the recommended refrigeration temperature range, how to ensure that the correct refrigeration temperature range is achieved, the importance of monitoring that it is being maintained, and the potential hazards of temperature abuse.

Keywords: chilled storage, food preservation, food safety, fridge, refrigerator

Introduction

The domestic refrigerator is a common, if not ubiquitous, household device throughout much of the world. There are very few households in the developed world that do not possess one for the storage of chilled foods. Refrigerators are reported to be one of the first assets, after a television, that a typical low-income household acquires as its wealth increases (Wolfram and others 2012). Take-up of refrigerators in developing countries has been related to urbanization, with ownership in China (an increasingly urbanized country) leaping from 24% in 1994 to 88% in 2014, whereas ownership in less urbanized countries, such as Peru and India, was only 45% and 25%, respectively, in 2014 (Anon 2014). The annual worldwide production of these appliances in 2009 was approximately 80 million units (Sim and Ha 2011), and there were estimated to be around 1 billion refrigerators in use worldwide in 2008, double the number 12 y earlier (Coulomb 2008).

Arguably, without the domestic refrigerator, the modern chilled food cold chain is not possible. Refrigeration is important in both maintaining the safety and quality of many foods and enabling food to be supplied and consumed in an increasingly urbanized world. As we argued in a previous review on the impact of climate change on the food cold chain (James and James 2010), it has been estimated that, throughout the world, less than 10% of perishable foodstuffs requiring refrigeration are, in fact, currently refrigerated (Coulomb 2008). Coulomb (2008) estimated that postharvest losses accounted for 30% of total production. More recent publications suggest similar or even higher losses. A study in the United States reported a 40% loss from farm to fork (Gunders 2012) and approximately 30% of all the food "for human consumption" was reported lost or wasted (Gustavsson and other 2011; FAO 2013). In China, only 15% of fresh produce was reported to be transported under refrigeration by Pang and others (2012) with "up to 30% of economic impact."

Although refrigeration uses energy, since the production of food involves a significant carbon investment, which is squandered if the food is then not utilized, then there is a balance to be achieved between energy consumption and waste. The International Institute of Refrigeration (2009) estimates that, in theory, if developing countries could acquire the same level of refrigerated equipment as that in industrialized countries, over 200 million metric tons of perishable foods would be preserved, this being roughly 14% of the current consumption in these countries. A study of food retailing in Nairobi, Kenya, showed that having a refrigerator increased the probability of households buying fresh fruits and vegetables at supermarkets by 31% (Neven and others 2006).

Many surveys have shown that temperature control in refrigerators may be inadequate (such as Evans and others 1991; Nauta and others 2003; Rahman and others 2005; Peck and others 2006; Gilbert and others 2007a; Godwin and others 2007; Vegara and others 2014). We have previously reviewed the performance of refrigerators (James and others 2008). Here, we build on that review, cover studies that have been published since (and those that

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were unfortunately missed in the first review), and also seek to put this important stage of the food cold chain in its proper context.

Recommended Refrigerator Temperatures

The official standards of the Codex Alimentarius Commission (2003) declare that insufficient food temperature control is one of the most common causes of foodborne illness. The World Health Organization (WHO) also states in its 5 keys to safer food that cooked food should not be left at room temperature for more than 2 h (in total), and that all cooked and perishable food should be quickly refrigerated below 5 °C (World Health Organization 2001). Recommended refrigerator temperatures vary throughout the world, but are below 7 °C (Terpstra and others 2005), with many countries recommending below 5 °C. In the United Kingdom, it is recommended that temperatures should be ≤5 °C (FSA 2015a), while in the U.S.A., a temperature ≤4.4 °C (40.0 °F) is recommended (USA FDA 2014). In 2007, IEC 62552:2007 "Household Refrigerating appliances – characteristics and test methods" was published (this has since been withdrawn): this included temperature performance standards including those for chilled compartments (Table 1). The relevance of these temperatures to the growth of microorganisms will be discussed in detail in a later section. Refrigerator temperatures also play a key role in minimizing food spoilage and waste.

Many countries have recommended operating temperatures that are not backed up by any legal requirements. However, some countries do have legal requirements. The French Government, for example, has required since 2002 that all domestic refrigerators must incorporate a chill compartment (with a mean temperature of ≤4 °C), a temperature-indicating device, and a temperature-regulating device (Peck and others 2006; Lagendijk and others 2008).

Householder Awareness of Temperatures

As Table 2 shows, surveys around the world have revealed that householders are often unaware of what temperature the food storage space in their refrigerator is recommended to be running at. Even those householders that are aware do not always put their knowledge into practice. Marklinder and others (2004) found that while 85% of Swedish respondents knew the correct recommended temperature, only 60% of the refrigerators surveyed were below the maximum recommended temperature, and only 25% of respondents knew, or regularly measured, the temperature of their refrigerators. Training has been shown to improve householder awareness and practices (Ghebrehewet and Stevenson 2003), although it is not known how long these changes in practice may last.

In addition, surveys have also shown that many householders do not know the temperature that their refrigerator is actually running at (Table 3). Most authorities recommend that householders use a fridge thermometer to check its temperature. A comprehensive assessment of different domestic refrigerator thermometers has been published by WRAP in the U.K. (George and others 2009). Many surveys have found that very few households own or use fridge thermometers (Table 4), and those that do often rarely check them or know where they should place the thermometer. For example, in a survey of 147 domestic refrigerators in Lebanon, not 1 participant had a thermometer to check the refrigerator temperature (Hassan and others 2015). While a U.S. survey of 200 refrigerators found that only 18 (9%) contained a thermometer, and that "for those homes where a thermometer was present in the refrigerator, the respondents reported that they rarely or never checked it" (Godwin and others 2007). In a survey across the Island of Ireland (Anon 2015a), only 6% of the refrigerators contained thermometers and only 2% of participants knew that their refrigerator had a thermometer.

Since 2002 it has been compulsory in France for manufacturers to fit domestic refrigerators with a type of device that indicates the temperature of the refrigerator (Anon 2002; Peck and others 2006; Lagendijk and others 2008). However, this does not appear to have had much impact on how often owners monitor their refrigerator temperature. A French survey in 1999 (Volatier 2000), carried out before the regulation, found that 33% of respondents monitored the temperature of their refrigerator, while a similar survey (Lagendijk and others 2008) carried out after the regulation in 2007 found that only 37% of the respondents monitored refrigerator temperatures.

In a survey across the Island of Ireland (Anon 2015a), it was reported that 69% of those surveyed did not know where (in the refrigerator) they "should place a fridge thermometer." Interestingly, the report fails to state where they would recommend placing a fridge thermometer, and a quick Google search by the authors has found that there is little advice to householders on where to place a fridge thermometer.

While fridge thermometers are widely recommended, Laguerre and others (2002) found that there was no statistical relationship between the temperature measured with a thermometer and that using a data-logger over a 7-d period. They concluded that temperatures measured using a thermometer did not represent the "true operating conditions of the refrigerator." A U.K. study (George and others 2010) also concluded that "a single-point temperature measurement in the fridge may not provide adequate information for the consumer." The authors recommended that 2 or 3 temperature points are used (top, middle, and bottom) so that the householder can ensure temperature-sensitive products (such as uncooked meats and pre-prepared foods) are placed in the coldest part of the refrigerator. This suggests that a more intelligent system for monitoring refrigerator temperatures is needed; one that provides more interactions with, and feedback to, the householder.

Temperatures in Domestic Refrigerators

Most studies that have looked at temperatures in refrigerators have surveyed refrigerators in households during use. A small number of studies have looked in detail at how refrigerators perform under controlled laboratory conditions.

Under domestic conditions

Numerous surveys over the last 30 y have studied how chilled foods are stored, handled, and prepared in the home (Table 5), with air or product temperatures in domestic refrigerators measured in a subset of these shown in Table 6 and 7. In some of these surveys, it is very clear how the temperatures were measured, where the sensors were positioned, and for how long the measurements were carried out (Table 8). While in others, far less data are provided so, unfortunately, results may not be strictly comparable.

Many studies have simply recorded spot temperatures; the researchers simply placed a single-point device in the refrigerator (often in the middle of the middle shelf) for 10 min to 1 h and then recorded the temperature. While this approach is understandable, given the logistical difficulties of measuring temperatures over time in numerous refrigerators, spot temperatures may not represent the mean temperature, as shown by Laguerre and others (2002). Studies, such as those by Koutsoumanis and Taoukis (2005), that

Table 1–IEC 62552:2007-specified domestic refrigerator storage temperatures (IEC 2007).

Compartment:	Fresh food storage compartment	Chill compartment	Cellar compartment
Definition:	Compartment intended for the storage of unfrozen food at the temperature specified	Compartment intended specifically for the storage of highly perishable foodstuff in which the above-specified storage temperature can be maintained	Compartment intended for storage of particular foods and beverages at a temperature warmer than that of the fresh food compartment
Temperature range:	0 to 8 °C (mean ≤ 4 °C)	−2 to +3 °C	+8 to +14 °C

Table 2–Householder awareness of the correct refrigerator operating temperature.

% of respondents with no knowledge of the correct recommended refrigerator temperature	N =	Country	Reference
88	50	New Zealand	O'Brien (1997)
67.7	1203	Australia	Jay and others (1999)
68.3	903	United Kingdom	Ghebrehewet and Stevenson (2003)
20	52	New Zealand	NZ Foodsafe Partnership (2004)
15.0	102	Sweden	Marklinder and others (2004)
78.0	1020	Ireland	Kennedy and others (2005a)
44.9	1030	Slovenia	Jevšnik and others (2008)
65.2	2332	Canada	Nesbitt and others (2009)
21	329	United Kingdom	George and others (2010)
54	3136	United Kingdom	Prior and others (2011)
44	100	Serbia	Đurić and others (2013)
47	3231	United Kingdom	Prior and others (2013)
75	100	Island of Ireland	Anon (2015)

Table 3–Householder awareness of their refrigerator operating temperature.

% of respondents with no knowledge of the temperature of their refrigerator	N =	Country	Reference
84.5	1203	Australia	Jay and others (1999)
76.0	102	Sweden	Marklinder and others (2004)
65.3	121	Trinidad	Badrie and others (2006)
43.7	1020	Slovenia	Jevšnik and others (2008)
60.6	1090	Turkey	Karabudak and others (2008)
63	809	France	Lagendijk and others (2008)
82.6	2332	Canada	Nesbitt and others (2009)
55.2	116	Slovenia	Ovca and Jevšnik (2009a)
87.9	33	Spain	Garrido and others (2010)
75	524	India	Joshi and others (2010)
43	2000	Norway	Røssvoll and others (2010)
48	3163	United Kingdom	Prior and others (2011)
48	3231	United Kingdom	Prior and others (2013)
53	100	Island of Ireland	Anon (2015)

have monitored temperatures continuously, note major temperature variations throughout the refrigerator for both position and time. Thus, studies that have monitored temperatures in many places for more than a week are more likely to provide an accurate measurement of a refrigerator's temperature performance.

In their analysis of past surveys, Peck and others (2006) concluded that 61% of refrigerators throughout the world run at mean air temperatures above 5 °C. We would estimate that factoring in recent surveys, this could be revised to about 54%, with about 66% operating at mean air temperatures above 4 °C. A review of European studies (7 studies in total) in 2003 concluded that, overall, the mean air temperature in European refrigerators would appear to be 6.6 °C (Nauta and others 2003). Refrigerator temperatures in northern countries of Europe are usually lower than those recorded in southern countries (Nauta and others 2003). The overall weighted arithmetic mean of mean air temperatures measured in the 35 surveys throughout the world collected in Table 6 is 6.1 °C.

While overall mean air temperatures (Table 6) are a convenient measure with which to compare refrigerator temperatures (particularly when hundreds of refrigerators are being compared), it only tells part of the story.

Few studies have analyzed the percentage of time refrigerators spent between different temperatures. Evans and others (1991) found that air temperatures in refrigerators they surveyed were between 3 and 8.9 °C for 80% of the time. Only 1.6% (4) of the refrigerators were found to be operating below 5 °C during the entire monitoring period, while 33.3% of the refrigerators were always above 5 °C. Similarly, Godwin and others (2007) reported that air temperatures rose above 4.4 °C for more than 2 h a day in the top shelf, middle shelf, and door of 33%, 45%, and 80%, respectively, of refrigerators they surveyed.

Effect of refrigerator design. There are 3 main types of refrigerator design: icebox refrigerators that have a box-plate evaporator within the refrigerator; larder refrigerators that have a backplate evaporator; fridge-freezers that have a backplate evaporator like

Table 4–Householder use of fridge thermometers.

% of respondents with a temperature measurement device	N =	Country	Reference
0	50	United States	Van Garde and Woodburne (1987)
23	1020	Ireland	Kennedy and others (2005a)
2	122	New Zealand	Gilbert and others (2006)
16	25	United Kingdom	Breen and others (2006)
24.7	81	United States	Towns and others (2006)
9	200	United States	Godwin and others (2007)
10.7	2060	United States	Kosa and others (2007)
7	154	United States	Byrd-Bredbenner and others (2007)
9	329	United Kingdom	George and others (2010)
16	3163	United Kingdom	Prior and others (2011)
14	3231	United Kingdom	Prior and others (2013)
6	100	Island of Ireland	Anon (2015)
0	147	Lebanon	Hassan and others (2015)
5	100	Serbia	Janjić and others (2015a)

Table 5–Published surveys of domestic storage of chilled foods carried out throughout the world in date order.

World region	Country	Reference
Africa	Nigeria	Oluwafemi and others (2015)
Americas	United States	Maxcy (1979); van Garde and Woodburne (1987); van de Reit (1985); Daniels (1998); Audits International (1999); Redmond and Griffith (2003); Godwin and others (2007); Byrd-Bredbenner and others (2007); Staskel and others (2009)
	Mexico	Macías-Rodríguez and others (2013)
Asia	China	Shixiong and Jing (1990)
	Malaysia	Rahman and others (2005); Saidur and others (2008)
	Lebanon	Hassan and others (2015)
	Iran	Maktabi and others (2013)
	India	Joshi and others (2010)
	Korea	Bahk (2010)
Europe	United Kingdom	Rose and others (1990); Evans and others (1991) (Evans 1992; James and Evans 1992a, 1992b); Worsfold and Griffith (1997); Johnson and others (1998); Ghebrehewet and Stevenson (2003); Breen and others (2006); Geppert and others (2010); George and others (2010); Brennan and others (2013); Evans and Redmond (2015)
	Northern Ireland	Flynn and others (1992)
	Island of Ireland	Anon (2015)
	France	Victoria (1993) (cited by Laguerre and others 2002); Derens and others (2001)a: Laguerre and others (2002); Lagendijk and others (2008); Geppert and others (2010); Carpentier and others (2012)
	The Netherlands	Lezenne Coulander (1994) (cited by Notermans and others 1997); Te Giffel and others (1997); Terpstra and others (2005)
	Germany	Geppert and others (2010)
	Greece	Sergelidis and others (1997); Koutsoumanis and Taoukis (2005); Taoukis and others (2005)
	Sweden	Marklinder and others (2004)
	Ireland	Kennedy and others 2005a
	Italy	Roccato (2013); Vegara and others (2014)
	Norway	Røssvoll and others (2014)
	Portugal	Azevedo and others (2005); Galvão and others (2016)
	Serbia	Durić and others (2013); Janjić and others (2015a)
	Spain	Carrasco and others (2007); Geppert and others (2010); Garrido and others (2010)
Oceania	Australia	Jay and others (1998) (cited by Gilbert and others 2007a); Jay and others (1999); Anon (2009)
	New Zealand	NZ Foodsafe Partnership (2004); Gilbert and others (2007a)

[a] in French, same study as Laguerre and others (2002).

a larder refrigerator (they can also have either 1 compressor supplying both refrigerator and freezer, or 2 separate compressors). Often surveys also make the distinction as to whether a refrigerator is an undercounter or tall refrigerator (both subsets of icebox and larder design refrigerators), or whether the refrigerator is an "American-style" fridge-freezer (a type of fridge-freezer design in which the refrigerator and freezer are fitted side-by-side rather than on top). In the U.K., combined fridge-freezers are the most popular format (Mintel 2013). Surveys have shown this to be also the case in France (Laguerre and others 2002) and Serbia (Janjić and others 2015a).

Some studies have found there to be a difference between the performances of different designs of refrigerator. In the Evans and others (1991) study, icebox refrigerators had the smallest temperature range (mean 1.8 °C), whereas the range of temperature in fridge-freezers and larder refrigerators was nearly twice as great (mean of 3.4 °C in fridge-freezers and 3.7 °C in larder refrigerators). Laguerre and others (2002) found that temperatures were more homogeneous in small refrigerators, due to the small volume of the refrigerated compartment. The greatest range of temperature (difference between top, middle, and bottom temperatures) was observed for fridge-freezers (with the freezer on the bottom). They postulated that this may be explained by the wide range of models of this design that are available. A survey by George and others (2010) found that air temperatures were higher in the refrigerator section of fridge-freezers with the refrigerator below in comparison with fridge-freezers with the refrigerator section on top. A recent Serbian survey (Janjić and others 2015a) found that icebox refrigerators had significantly lower mean air temperatures (7.1 °C) than frost-free refrigerators (9.0 °C) and fridge-freezers (9.7 °C). Not all studies have found differences between different types of refrigerators. For example, that carried out in the Island

Table 6–Air temperatures measured in surveys of domestic refrigerators in homes.

Country	N =	Temperature (°C) Min	Mean	Max	Reference
United States	11		3.6 [a]		Maxcy (1979)
United Kingdom	75		<5	15	Rose and others (1990)
United Kingdom	252	0.9	6.0	11.4	Evans and others (1991)
Northern Ireland	150	0.8	6.5	12.6	Flynn and others (1992)
France	102			14	Victoria (1993) [b]
New Zealand	50	0	4.9	11	O'Brien (1997)
The Netherlands	334	−1	7.4	17.9	Te Giffel and others (1997)
United Kingdom	108	2	5.9	12	Worsfold and Griffith (1997)
United Kingdom	645	−2	7	13	Johnson and others (1998)
United States	939	−6	4	21	Audits International (1999)
France	119	0.9	6.6	11.4	Derens and others (2001); Laguerre and others (2002)
New Zealand	53	−2.5		9.9	NZ Foodsafe Partnership (2004)
Ireland	100	−7.9	5.4	20.7	Kennedy and others (2005a)
Malaysia	26	2.0	7.3	14.0	Rahman and others (2005)
Greece	250	−2	6.3		Taoukis and others (2005)
Netherlands	31	3.8		11.5	Terpstra and others (2005)
United Kingdom	24		5.0 (mode)		Breen and others (2006)
Spain	30		6.6		Carrasco and others (2007)
United States	151		6.1		Byrd-Bredbenner and others (2007)
New Zealand	127	−4.9	5.2	18	Gilbert and others (2007a)
Australia	57		3.6	9.5	Anon (2009)
United States	6	8		12	Staskel and others (2009)
Korea	139	−5.1	3.5	14.4	Bahk (2010)
United Kingdom	23	−1.9	8.2	18	Brennan and others (2013)
United Kingdom	329	1.0	5.9	15.0	George and others (2010)
United Kingdom	50	1.0	7.0	>10.0	George and others (2010)
Germany	100	0	6.2	11	Geppert and others (2010)
United Kingdom	100	3	5.2	10	Geppert and others (2010)
France	100	1	6.7	12	Geppert and others (2010)
Spain	100	0	4.1	10	Geppert and others (2010)
Spain	33	0.6	7.9	14.5	Garrido and others (2010)
France	19	1.4	6.6	11.0	Carpentier and others (2012)
Serbia	100	−1.9	9.0	20.8	Durić and others (2013)
Italy	106		7.2		Roccato (2013)
Norway	46	1.3	5.6	9.9	Røssvoll and others (2014)
Italy	660	2.5	8.1	15.9	Vegara and others (2014_
Island of Ireland	98	−4	4.9	12.5	Anon (2015)
United Kingdom	100	0.2	6.2	17.4	Evans and Redmond (2015)
Lebanon	147	−5.9	8.0	37.0	Hassan and others (2015)
Serbia	100	−1.9	9.3	21.3	Janjić and others (2015a)
Portugal	51	−6	5.5	18.5	Galvão and others (2016)
All (weighted mean of means)	5888	−1.5	6.1	16.1	

[a] measured in water containers in refrigerator.
[b] cited by Laguerre and others (2002).

of Ireland (Anon 2015) found no significant difference between the performance of different types.

Effect of position within refrigerator. Householders are often told where they should store their food. For example, U.K. recommendations from the FSA (2015a) are that the top shelves and middle shelves should be used for ready-to-eat foods "such as dairy products, yogurts, cream, cream cakes, butter/margarine, cooked meats, leftovers-covered, [and] other packaged foods (coleslaw, tomato ketchup, jams)," the bottom shelves should be used for raw meat, poultry, and fish, while salad vegetables, fruits, and vegetables should be kept in the salad drawer.

A number of surveys have asked householders where in the refrigerator, they store certain foods. Most studies have found that the majority of respondents would usually place raw meat or poultry on the bottom shelf of the refrigerator (Table 9). This is in line with most published advice (such as FSA 2015a and FSAI 2015). However, some surveys (Marklinder and others 2004; Ovca and Jevšnik 2009a; Geppert and others 2010) have reported a majority preference for storing raw meats on the top or middle shelves. Some of these surveys appear to have only given respondents the option of the bottom, middle, and top shelf as a response to where they store raw meats. In surveys where other options were possible, a significant number of respondents profess to having no preference (7 to 14%), often storing raw meat "wherever there is space."

There is often an assumption that, since heat rises upward, higher temperatures will be found toward the top of the refrigerator. A number of studies have made this assumption when asking householders where they store certain foods. For example, a recent Irish survey (Anon 2015) reports that "almost half of the participants (44%) correctly identified the bottom shelf as the coldest part of a fridge." This survey making the presumption that the bottom shelf is always the coldest position within the refrigerator. In contrast, both a Swedish (Marklinder and others 2004) and a Slovenian (Ovca and Jevšnik 2009a) survey found that the majority of respondents believed that the coldest position in the refrigerator to be the top shelf.

Surveys have shown that the position of the highest and lowest temperatures within a refrigerator is not consistent (Table 10). Both Evans and others (1991) and a 2004 New Zealand survey (NZ Foodsafe Partnership 2004) found that the top shelf was the warmest position in almost 3 quarters of the refrigerators surveyed.

Table 7–Reported values of air temperatures measured in surveys of domestic refrigerators in homes.

		Temperature (°C)									
Country	N =	≤4	≤5	>4	>5	>6	>7	>8	>9	>10	Reference
United States	50	34		67						21	Van Garde and Woodburne (1987) (Van De Reit 1985)
United Kingdom	75		94		6						Rose and others (1990)
United Kingdom	252		30		70						Evans and others (1991)
Northern Ireland	150		29		71						Flynn and others (1992)
France	102					70					Victoria (1993) [a]
The Netherlands	125		30				28		2		Lezenne Coulander (1994) [b]
New Zealand	50			60							O'Brien (1997)
Greece	136								50	25	Sergelidis and others (1997)
The Netherlands	334						57				Te Giffel and others (1997)
United Kingdom	108				50						Worsfold and Griffith (1997)
United States	106				69						Daniels (1998)
Australia	85				32						Jay and others (1998) [c]
United Kingdom	645				70						Johnson and others (1998)
United States	939				27		8			2	Audits International (1999)
France	119				80						Derens and others (2001); Laguerre and others (2002)
United Kingdom	901	69.3		30.7						2.8	Ghebrehewet and Stevenson (2003)
New Zealand	53		43.4				7.5				NZ Foodsafe Partnership (2004)
Greece	110	26		74		46		23		8	Bakalis and others (2003)
Portugal	86	13		87		70		39		12	Azevedo and others (2005)
Ireland	100				59					6	Kennedy and others (2005a)
Malaysia	26	7	27		59	54	38				Rahman and others (2005)
Greece	250					50				10	Taoukis and others (2005)
Netherlands	31						68				Terpstra and others (2005)
United Kingdom	24					33					Breen and others (2006)
United States	2060	72		28							Kosa and others (2007)
	200	91 (T)			9 (T)		0 (T)			0 (T)	
		79 (B)			21 (B)		3.7 (B)			1.6 (B)	
United States		45 (D)			55 (D)		13 (D)			1 (D)	Godwin and others (2007)
New Zealand	127				55	34					Gilbert and others (2007a)
United Kingdom	48	35	54		65	46	27	15	4	2	George and others (2010)
Serbia	100			94							Durić and others (2013)
Mexico	200	11		89			53				Macías-Rodríguez and others (2013)
Iran	180		26		74			22			Maktabi and others (2013)
Italy	660	6					73.8			51.2	Vegara and others (2014)
Island of Ireland	98		58								Anon (2015)
United Kingdom	100				50						Evans and Redmond (2015)
Lebanon	147					71					Hassan and others (2015)
Serbia	100			92							Janjić and others (2015a)
Nigeria	180	29.4		70.6							Oluwafemi and others (2015)

[a] cited by Laguerre and others (2002).
[b] cited by Notermans and others (1997).
[c] cited by Gilbert and others (2007a).

However, Godwin and others (2007) found that recommended mean temperatures (≤4.4 °C) were measured in 91% of the top shelves but only 79% of bottom shelves. Those surveys that have measured temperatures in the door usually find that this position to have the highest temperature (Table 9). Bakalis and others (2003) were unable to unilaterally define the location of the coldest position, noting that in "some refrigerators, the lower temperature was observed in the middle position, while in others in the upper tray." In all cases, they found a difference of more than 5 °C between different positions in the same refrigerator. Laguerre and Flick (2004) found that the highest temperature position within a refrigerator could change with time. Within the same refrigerator, they found that at times the highest temperature was at the top, whereas at other times, it was in the middle.

Effect of age and condition. In general, refrigerators are very reliable, so it is not surprising that many surveys have shown that a significant number of household refrigerators are over 10 y old (Table 11). Some surveys have reported that age (Anon 2009;

Table 8–Methods used to measure air temperatures in surveys of domestic refrigerators.

Country	Number of samples	Measurement	Positions	Where (Top shelf (T), Middle shelf (M), Bottom shelf (B), Door (D))	Reference
United States	11	Thermometer	1	Not known	Maxcy (1979)
United States	50	Thermometer	1	M	Van Garde and Woodburne (1987) (Van De Reit 1985)
United Kingdom	75	Not known	Not known	Not known	Rose and others (1990)
United Kingdom	252	Data logger	3	T, M, B	Evans and others (1991)
Northern Ireland	150	Thermometer	3	T, M, B	Flynn and others (1992)
France	102	Thermometer	3	T, M, B	Victoria (1993) [a]
The Netherlands	125	Thermometer			Lezenne Coulander (1994) [b]
New Zealand	50	Thermometer	2	T, B	O'Brien (1997)
Greece	136	Thermometer	1	Not known	Sergelidis and others (1997)
The Netherlands	334	Digital thermometer	1	Product	Te Giffel and others (1997)
United Kingdom	108	Data logger	1	Not known	Worsfold and Griffith (1997)
United States	106	Not known	Not known	Not known	Daniels (1998)
Australia	Not known	Not known	Not known	Not known	Jay and others (1998) [c]
United Kingdom	645	Thermometer	1	T (icebox refrigerators), B (larder refrigerators	Johnson and others (1998)
United States	939	Digital thermometer	Not known	Product	Audits International (1999)
France	119	Data logger	3	T, M, B	Derens and others (2001); Laguerre and others (2002)
United Kingdom	901	Not known	1	Not known	Ghebrehewet and Stevenson (2003)
Sweden	102	Product temperatures	Not known	Product	Marklinder and others (2004)
New Zealand	53	Not known	Not known	Not known	NZ Foodsafe Partnership (2004)
Greece	110	Data logger	4	T, M, B, D	Bakalis and others (2004)
Portugal	86	Digital thermometer	1	Not known	Azevedo and others (2005)
Ireland	100	Data logger	1	M	Kennedy and others (2005)
Malaysia	26	Data logger	3	T, M, B	Rahman and others (2005)
Greece	250	Data logger	Not known	Not known	Taoukis and others (2005)
Netherlands	31	Glass thermometer	1	Water in door	Terpstra and others (2005)
United Kingdom	25	Glass thermometer in gel	1	Not known	Breen and others (2006)
Spain	30	Data logger	1	Not known	Carrasco and others (2007)
United States	151	Digital thermometer	1	Not known	Byrd-Bredbenner and others (2007)
United States	200	Data logger	3	T, B, D	Godwin and others (2007)
New Zealand	127	Data logger	2	T, B	Gilbert and others (2007a)
United States	2060	Refrigerator thermometer	1	M, back	Kosa and others (2007)
United States	6	Not known	Not known	Not known	Staskel and others (2009)
Korea	139	Data logger	Not known	Not known	Bahk (2010)
Spain	33	Thermometer	3	T, M, B	Garrido and others (2010)
United Kingdom	329	Thermometer	1		George and others (2010)
United Kingdom	50	Data logger	3	T, M, B (salad crisper)	George and others (2010)
Germany /United Kingdom/France/Spain	100	Data logger	1	M	Geppert and others (2010)
France	19	Data logger	2	M, B	Carpentier and others (2012)
United Kingdom	23	Data logger	1	D	Brennan and others (2013)
Serbia	100	Data logger	3	T, B, D	Durić and others (2013)
Mexico	200	Digital thermometer	1	M	Macías-Rodríguez and others (2013)
Iran	180	"Normal thermometer"	1	Not known	Maktabi and others (2013)
Italy	106	Data logger	3	T, B, D	Roccato (2013)
Norway	46	Data logger	1	By products	Røssvoll and others (2014)
Italy	660	Recording digital thermometer	1	M	Vegara and others (2014)
Island of Ireland	98	Digital thermometer	1	M	Anon (2015)
United Kingdom	100	Digital thermometer	2	M, D	Evans and Redmond (2015)
Lebanon	147	Data logger	1	M	Hassan and others (2015)
Serbia	100	Data logger	3	T, B, D	Janjić and others (2015a)
Nigeria	180	Thermometer	1	Not known	Oluwafemi and others (2015)
Portugal	51	Data logger	1	M	Galvão and others (2016)

[a] cited by Laguerre and others (2002).
[b] cited by Notermans and others (1997).
[c] Cited by Gilbert and others (2007a).

Table 12) and door seal condition (O'Brien 1997; Anon 2009) have a significant influence on the temperature of a refrigerator. However, other surveys (O'Brien 1997; Hassan and others 2015; Janjić and others 2015a) have found no correlation between refrigerator temperature and age of refrigerator. Hassan and others' (2015) survey of 147 Lebanese refrigerators showed that higher temperatures were only associated with refrigerators that were older than 19 y. Janjić and others (2015a) found that the overall mean temperature was lower, 8.7 °C compared to 9.5 °C in the 19 refrigerators they surveyed that were over 10 y old, in comparison with the 45 refrigerators that were less than 5 y old, respectively.

Effect of door openings. It is generally recognized that the frequency and length of door opening will have an effect on the temperature performance of a domestic refrigerator. Both Laguerre and others (2002) and Rahman and others (2005) found a direct relationship with the frequency of door opening and

Table 9–Where households store raw meats (%).

Top shelf	Middle shelf	Bottom shelf	No particular place	*N* =	Country	Reference
30	47	21		100	Sweden	Marklinder and others (2004) [a]
13	10	53		1020	Ireland	Kennedy and others (2005a)
11.1	25.9	55.6		81	United States	Towns and others (2006)
		62.5	7.6	326	New Zealand	Gilbert and others (2007b)
42.2	13.8	20.7	13.8	116	Slovenia	Ovca and Jevšnik (2009a)
30	45	21.8		100/100/100/100	Germany / United Kingdom / France / Spain	Geppert and others (2010)
38				524	India	Joshi and others (2010)
23	7	62	10	3163	United Kingdom	Prior and others (2011)
7	8	61	8	3231	United Kingdom	Prior and others (2013)
		70	7	100	Island of Ireland	Anon (2015)

[a] Actual positions where householders stored ground beef.

Table 10–Air temperatures measured at different positions in domestic refrigerators.

Mean air temperature (°C)					
Top	Middle	Bottom	Door	*N* =	Reference
6.7	6.4	6.5		720 to 119	Derens and others (2001); Laguerre and others (2002)
9.0		8.6	10.4	100	Durić and others (2013)
	6.0		7.0	100	Evans and Redmond (2015)
5.9	4.7	9.6[a]		50	George and others (2010)
5.8		4.5		127	Gilbert and others (2007a)
1.9		3.3	5.2	98, 187, 197	Godwin and others (2007)
9.0		8.6	10.4	100	Janjić and others (2015a)
6.9		6.6	8.0	106	Roccato (2013)

[a] Salad crisper.

Table 11–Age of refrigerators.

	% of refrigerators of a certain age (years)						
Country	<2	<4	<5	<6	5 to 10	>10	>12	Reference
France		51			35		14	Laguerre and others (2002)
Malaysia		24			68	8		Rahman and others (2005)
New Zealand						41		Gilbert and others (2007a)
France	19		51		29	16		Lagendijk and others (2008)
New Zealand	50		28		12	60		O'Brien (1997)
Sweden			40		22	19		Marklinder and others (2004)
Malaysia			26		44	30		Saidur and others (2008)
Australia			30		34	34		Anon (2009)
United Kingdom	21	51	67		31			George and others (2010)
France			48		22	30		Carpentier and others (2012)
Island of Ireland			52			19		Anon (2015)
Lebanon				37.4			30.8	Hassan and others (2015)
Serbia			45		36	19		Janjić and others (2015a)
Nigeria			60 to 90 [a]			10 to 40 [a]		Oluwafemi and others (2015)

[a] depending on region.

refrigerator temperature. Not surprisingly, they both found that higher temperatures were related to a higher number of door openings. Hassan and others (2015) found that mean refrigerator temperatures were about a degree higher during the day (6 am to 6 pm) and attributed this to a higher frequency of door openings. However, few surveys have tried to measure the frequency and duration of door opening or to quantify the effect of this on refrigerator performance under normal household use. Some of the studies have looked at the effect of door opening on energy consumption rather the temperature performance (Gage 1995; Meier 1995; Saidur and others 2008). An early study by Torrey and Marth (1977) of 2 household refrigerators showed frequencies of door opening of 9 and 18 times a day. Mean recovery times for the refrigerators after opening ranged from 5.4 to 13.9 min. While Chang and Grot (1979), in a study of 10 household refrigerators, found that the door was opened on average 48 times per day, with a mean opening time of 21 s. Meier (1995) estimated that "typical households will open the refrigerator 40 to 60 times per day," however, it is unclear what evidence this was based on. Gage (1995) and Geppert and others (2010) reported means of 10 and 11 door openings per day, respectively, with Gage (1995) also reporting a mean opening time of 10 s. Laguerre and others (2002), Rahman and others (2005), and Saidur and others (2008) used questionnaires to capture data on door opening (Table 13). Rahman and others (2005) reported a much higher incidence of door openings during the day than Laguerre and

Table 12–Comparison of refrigerator performance and age (adapted from Anon 2009).

Age (years)	N =		Age (years)	Mean (°C)	Median (°C)	Min (°C)	Max (°C)
<5	15	Mean	2.8	2.6	2.5	0.4	5.5
		Range	0.5 to 5	1.0 to 4.7	1.0 to 4.5	−5.0 to 3.5	3.0 to 9.0
5 to 10	16	Mean	8.3	3.5	3.3	0.8	7.9
		Range	6 to 10	0.1 to 9.5	0.0 to 9.0	−4.5 to 8.5	1.0 to 20.5
>10	16	Mean	15.9	4.3	4.2	1.9	8.1
		Range	11 to 24	1.2 to 9.5	1.0 to 8.5	−4.0 to 7.5	3.0 to 20.0

Table 13–Frequency of door openings.

# of door openings per day					
<10	10 to 20	>20	>30	N =	Reference
			35	60	Evans (1998)
19	43	38		143	Laguerre and others (2002)
8	19	73		26	Rahman and others (2005)
17	39	44		104	Saidur and others (2008)

others (2002) or Saidur and others (2008). As may be expected, both surveys by Laguerre and others (2002) and Rahman and others (2005) found that global refrigerator temperatures were higher in refrigerators with a high frequency of door openings (Saidur and others 2008 monitored energy consumption and not temperature performance). In a cross-Europe web-based survey (covering respondents in Germany, U.K., France, and Spain), most respondents stated that they opened the refrigerator up to 15 times a day (Geppert and Stamminger 2010). Although they did not record door openings in their survey.

In a follow-up of Evans and others' (1991) U.K. survey, the effect of door openings upon temperature performance under normal household use was investigated in 60 household refrigerators and measured over a period of between 3 and 7 d (Evans 1998). Households were found to vary widely in their refrigerator use: 65% of households opened the refrigerator fewer than 30 times per day and 70% opened the door for a total of less than 4 min per day. On average, refrigerator doors were open for 7.3 s (range 1 to 31 s) with a mean of 39 door openings (range 1 to 240) and a total door opening time of 3.1 min per day (range 0.2 to 11.5 min). This number of door openings is similar to Meier's (1995) estimate but far greater than that measured by many of the other published studies discussed above. There was no apparent relationship between the number of times the refrigerator door was opened and the duration the door was open during a day. Overall, there was a poor correlation between either the number of door openings or the total length of time the door was open per day, and the mean air temperature at any position within a refrigerator or the mean food temperatures. A relationship was found between the total number of door openings per day and the maximum temperature measured in larder refrigerators, indicating that larder refrigerators may be more sensitive to door opening time than other refrigerator types.

A recent study by Bennan and others (2013) used "Activity recognition and temperature monitoring (ART)" systems to monitor refrigerator temperatures and use (door openings). The ART systems were able to monitor light and movement in order to record door openings and were mounted on the doors of the refrigerators being monitored. The minimum and maximum numbers of door openings per day in the 23 refrigerators monitored were 1 and 60, respectively. The mean number of door openings per day ranged from 9 to 32, with opening times ranging from 1 to 61 s. The average door opening time was 12 to 33 s. The refrigerator took from 1 to 123 s to recover to within 5% of the starting temperature after a door opening.

It may be assumed that there will be some relationship between the number of door openings and size, type, and lifestyle of household. To our knowledge, no survey appears to have investigated these factors in any detail.

Some new refrigerators have been designed with alternative door designs that help to minimize the effect of door openings, such as "American-style" refrigerators that have small doors that can be opened to allow access to frequently needed items, keeping the rest of the refrigerators sealed (George and others 2010). Other refrigerators incorporate door alarms to alert the user if the door of the refrigerator is left open. After-market refrigerator alarms are also available in a multitude of forms. We are unaware of any studies that have been carried out to investigate whether these alarms change how households use their refrigerators or whether they improve the temperature control of household refrigerators.

Under controlled conditions

In our previous review (James and others 2008), we found that few studies have been published on the temperature performance of domestic refrigerators under controlled conditions, a few more studies have been published since our review in 2008. More data measured under controlled conditions can be found on energy consumption (Dlugoszewski and Minczewski 1984; Hermes and Melo 2009; Hermes and others 2009), evaporator coil design (Karpinski 1984), improving performance by incorporating phase change materials (Khan and Afroz 2015; Yusufoglu and others 2015), and the shelf-life advantages to be gained with product stored in a special refrigerator containing a 0 °C chamber with fan air circulation (Olsson 1988). The standard for domestic refrigerators (EN 62552:2013) contains some temperature tests that are carried out under controlled conditions on empty, closed refrigerators. As may be expected, studies under controlled conditions (Saidur and others 2002; Liu and others 2004; Khan and Afroz 2014) have shown that the frequency of door openings has a significant effect on energy consumption and internal temperatures.

As discussed in our previous review on refrigerators (James and others 2008), some data were published from experiments carried out on examples of 3 types of refrigerator by James and Evans (1992b). These were a dual-compressor fridge-freezer, a single compressor fridge-freezer, and a freestanding domestic icebox refrigerator. When tested empty and set to the manufacturers recommended setting, temperatures in the icebox refrigerator were uniform and low, with a minimum of −1.4 °C on the bottom shelf and a maximum of 5.9 °C in the door. There was a much larger temperature range in the 2 fridge-freezers: 1.7 to 14.3 °C in one and −6.7 to 10.7 °C in the other. Mean temperatures were far less uniform in the chilled food compartment of the fridge-freezers. Filling the refrigerators with packs of a simulated food ("Tylose," the Karlsruhe test substance) changed the air temperatures, the distribution of temperature, and the refrigeration cycle time. In the icebox refrigerator, the mean air temperatures decreased by between 1.2 and 2.0 °C. In one of the fridge-freezers, the mean temperature of the top shelf rose by 0.7 °C and the other positions dropped by between 0.5 and 1.1 °C. In the other fridge-freezer, the magnitude of the temperature cycle was substantially reduced, and the warmest position in the refrigerator shifted. When empty, the maximum temperature was 14.3 °C, and on the top shelf, after filling the maximum measured temperature dropped to 9.8 °C and was recorded on the bottom shelf.

Laguerre and Flick (2004) analyzed heat transfer by natural convection in a domestic larder refrigerator. They measured the air temperatures within the refrigerator at 25 locations. The mean air temperature measured over 24 h was 6.3 °C, with a minimum value of 3.8 °C and a maximum of 8.3 °C. There was a wide variation in temperatures in different areas of the refrigerator. The highest mean wall temperature of 9.1 °C was measured at the top, whereas middle and bottom temperatures were 5.4 and 5.7 °C, respectively.

The air temperature and humidity levels within 6 refrigerators, representing a range of designs (Table 14), were tested under controlled conditions as part of a laboratory study in the U.K. funded by WRAP (George and others 2010). During the experiment, the 6 refrigerators were set to provide a nominal refrigerator air temperature of 5 °C and maintain a mean temperature distribution below 5 °C. Wide variations of air temperatures were measured at different points in the cabinet (Table 14). The study found that refrigerators with glass shelves were better able to maintain a more consistent air temperature within the cabinet and to minimize any rapid rise in air temperature than those with wire shelves. This is the only study we have found that has compared, or recorded, the effect of different shelf designs.

Ovca and Jevšnik (2009b) studied the effects of power failure on refrigerator temperatures under controlled conditions. They used a larder refrigerator. They found that the external environmental temperature during a power failure had more of an effect on internal refrigerator temperatures than opening the door, provided that the door was opened infrequently for only 10 s (the authors assumed that during a power-cut householders would be careful not to access their refrigerator too often). Eutectic plates or ice banks can be used to stabilize temperatures where power supply is intermittent, as used by The Sure Chill Company (Lynch 2014).

Hygienic Status of Domestic Refrigerators

Improper food handling, storage, and ineffective hygiene by householders are often cited as causes for food poisoning in the home (Redmond and Griffith 2003). However, we have found it difficult to find any recent hard data on the occurrence of food poisoning in the home. A number of different pathogenic bacteria have been found in kitchens, and specific sites, such as the refrigerator door handle (Haysom and Sharp 2006; Azevedo and others 2014), are often found to be the most highly contaminated. There has been much interest in the role of refrigerators in food poisoning in the home.

The only pathogens capable of growing at refrigerated temperatures below 5 °C are *Listeria monocytogenes* and *Yersinia enterocolitica*. Both pathogens are psychrotrophs and capable of growth at temperatures near 0 °C. As this review shows, many domestic refrigerators are operating above the recommended temperatures and therefore are capable of supporting suboptimum but significant growth of mesophilic organisms such as *Staphylococcus aureus* and *Salmonella* spp. (Schmitt and others 1990; Flynn and others 1992; Johnson and others 1998).

A number of studies have measured the prevalence of these pathogens in domestic refrigerators (Table 15). In general, these surveys have shown the prevalence of to be low, with the exception of data by Macías-Rodríguez and others (2013), and suggest that the interior of refrigerators is not a significant vector in the transmission of these pathogens. However, considering the number of refrigerators in use throughout the world, these prevailing conditions could still be significant.

As covered in our previous review on refrigerators (James and others 2008), Kennedy and others (2005a) found a higher general incidence of pathogens and aerobic plate counts (APCs) in urban householders' refrigerators than those of rural householders, and that householders under 25 y of age were more likely to have 1 or more pathogens present in their refrigerators. Interestingly, the refrigerators of households from socioeconomic group ABC1 had significantly higher APCs than those belonging to members of the C2DE group.

Smyth and others (2006) concluded that most Irish domestic refrigerators harbor enterotoxin-producing *S. aureus*. Other assessments have shown high APCs and coliform counts (Te Giffel and others 1997; Ojima and others 2002; Abdalla and others 2008; Kilonzo-Nthenge and others 2008; Macías-Rodríguez and others 2013; Oluwafemi and others 2015). Jackson and others (2007) found that almost a quarter of the refrigerators sampled yielded coliform contamination levels greater than 3 $\log_{10}$ CFU/cm^2.

Few studies have investigated whether the environment within the refrigerator is conducive to microbial growth. Humidity levels measured within 2 refrigerators (fridge-freezers) showed that, in general, the interior of a refrigerator is quite a dry environment, thus not an ideal environment for microbial growth (George and others 2010). Humidity cycles with air temperature and mean dew point temperatures were found to drop to −7 and −1 °C in each refrigerator during nighttime operation. This is unsurprising since the moisture in the air will condense on the coldest surface within the refrigerator, which will be the evaporator, where it is likely to freeze, it will then be drained away when defrosted (either manually or automatically).

Most consumer advice (such as USA FDA 2011, FSA 2015a, and FSAI 2015) recommends that refrigerators be cleaned frequently. Many surveys have highlighted how infrequently refrigerators are actually cleaned (Table 16). However, no survey appears to have been able to identify any clear link between refrigerator cleanliness and food poisoning. As cited in our previous review (James and others 2008), studies have shown that household kitchens with dirty refrigerators are no more likely to give rise to an episode of salmonella infection than clean kitchens (Parry and others 2002, 2005). Although Kennedy and others (2005b) found that "conscientious food handlers were statistically less likely to have higher TVCs (total viable counts), "any pathogen," and *S. aureus* or *Salmonella* Enterica in their refrigerator."

Food Storage and Use by Dates

As discussed in the previous section, the only pathogens capable of growing below recommended refrigerated temperatures (below 5 °C) are *L. monocytogenes* and *Y. enterocolitica*. Although since many refrigerators are running above the recommended temperatures

Table 14–Comparison of the performance of 6 refrigerators under controlled conditions (adapted from George and others 2010).

					Mean nighttime[a] operation air temperature (°C)		Mean daytime[b] operation air temperature (°C)	
Number	Type	Volume (*l*)	Energy rating (*w*)	Shelf	Lowest	Highest	Lowest	Highest
1	Fridge-freezer (fridge top)	152	100	Glass	1.8 (Middle, back)	9.3 (Top, front)	2.3 (Middle, back)	10.6 (Top, front)
2	Fridge-Freezer (fridge top)	135	85	Wire	5.0 (Middle, back)	8.7 (Top, front)	6.7 (Middle, back)	9.7 (Top, front)
3	Larder	135	55	Wire	1.4 (Middle, back)	9.1 (Door, top)	1.8 (Middle, back)	5.5 (Door, top)
4	Larder	135	55	Wire	4.8 (Middle, back)	8.4 (Door, bottom)	4.9 (Middle, back)	9.8 (Door, bottom)
5	Icebox	132	70	Wire	5.2 (Top, center)	10.5 (Salad drawer)	6.3 (Top, center)	11.0 (Top, front)
6	"American-style"	352	140	Glass	4.6 (Middle)	6.0 (Top)	4.6 (Middle)	6.5 (Top)

[a]No door opening.
[b]Door opened for 2 min each hour for 6 h.

Table 15–Prevalence of pathogens in domestic refrigerators.

% Incidence of							
L. monocytogenes	*Listeria innocua*	*Y. enterocolitica*	*Salmonella* spp.	*S. aureus*	N =	Country	Reference
			0.3	1.5	392	United Kingdom	Scott and others (1982)
0					195	United States	Jackson and others (1993)
2.9					35	The Netherlands	Cox and others (1989)
2.5	1.5				204	The Netherlands	Beumer and others (1996)
1.5					136	Greece	Sergelidis and others (1997)
3	1				86	Portugal	Azevedo and others (2005)
6		2	7	41	1020	Ireland	Bolton and others (2005)
0	1				60	France	Dieuleveux and others (2005)
1.2		0.6	0	6.4	342	Ireland	Jackson and others (2007)
3.8		1.6		9.54	150	Sudan	Abdalla and others (2008)
0	2.1				47	Brazil	De Souza and others (2008)
0	6	0.7			137	United States	Kilonzo-Nthenge and others (2008)
20.5 – 59.5			8.0 to 32.5		200	Mexico	Macías-Rodríguez and others (2013)
0.5	1.2				180	Iran	Maktabi and others (2013)
0	2.4				84	Italy	Vegara and others (2013)
0		0	1.4		293	Italy	Catellani and others (2014)
			13.95		86 [a]	Serbia	Janjić and others (2015b)
				75	170	Nigeria	Oluwafemi and others (2015)

[a]households that stored eggs in the refrigerator door.

other pathogens such as *S. aureus* and *Salmonella* spp. may also be capable of growth in foods in domestic refrigerators.

While risk assessments have been carried out that have modeled the potential for different pathogens to grow under domestic storage conditions, many of these studies (such as Lianou and others 2007; Garrido and others 2010; Røssvoll and others 2014) have grown pathogens under controlled conditions at mean temperatures that simulate mean temperatures reported in domestic refrigerators rather than reproducing the temperature fluctuations seen in domestic refrigerators. While some studies have examined growth and survival of pathogens in foods in domestic refrigerators, the details of refrigerators used and their temperature performance are not always clear. No practical studies appear to have compared the effects of different types of refrigerator, storage position within a refrigerator, rate, and time of door openings, among various factors, on actual growth/survival of pathogens under real or simulated conditions. Surveys of refrigerator temperatures have shown that temperature fluctuations in refrigerators with similar mean temperatures can be very different. To our knowledge, no studies have examined the impact of different temperature fluctuations and variations on the growth/survival of pathogens in household refrigerators.

Surveys suggest that foods associated with *L. monocytogenes* may be subject to prolonged domestic storage, which may increase the risk of illness (Evans and Redmond 2015). Examples of "higher" risk foods (Little and others 2012; FSA 2015b; NHS 2015) include soft, mold-ripened cheese (such as Brie and Camembert), soft blue-veined cheese (such as Danish blue, Gorgonzola, and Roquefort), any other cheeses made from unpasteurized milk, raw milk, butter, paté (including vegetable paté), cured meats (such as chorizo and salami), smoked fish (including salmon), shellfish, sliced cooked meats (including ham, beef, chicken), salads, fruits, vegetables, herbs, prepacked salads, sandwiches, rolls, and wraps that contain the above foods. In the U.K., consumer groups that are particularly vulnerable to listeriosis have been advised to avoid specific foods (FSA 2015b). The extent to which individuals in these vulnerable groups are vulnerable is variable, and thus the risk different foods present is variable. For example, although persons over 60 have been identified as a vulnerable group, persons who are over 60 and in "good health" are not as vulnerable as those who are infirm. Many of these higher-risk RTE foods have long shelf-lives and are sold in relatively thin consumer packs (particularly smoked salmon and sliced meats and cheese) that are likely to be affected more by cycling air temperatures in a domestic refrigerator than bulk-packed foods. Recent studies suggest that many older adults in the U.K. fail to adhere to recommendations to avoid such foods, and they may eat foods that are beyond their "use-by" date (also known as the "consume-by" or "expiration" date in some regions). In a survey by Evans and Redmond (2015), 68% of older adults were reported to store soft cheese in domestic

Table 16–How often householders clean the refrigerator.

Country	*N* =	Weekly	More than once per month	Monthly or less frequently	Every 3 mo or more	Every 2 to 3 mo	One or 2 times a year	Less than once a year	Reference
New Zealand	50	12	12	40					O'Brien (1997)
United States	609	14		40			34	5	Li-Cohen and Bruhn (2002)
Portugal	86	6		80					Azevedo and others (2005)
France	809		8	82		33		4	Lagendijk and others (2008)
India	524	15		25					Joshi and others (2010)
Germany	90	1.1	4.4	11.1		51.1		26.7	Ilg and others (2011)
France	23				57	43			Carpentier and others (2012)
Mexico	200	12	13	47	24		4		Macías-Rodríguez and others (2013)
Iran	180	1.7	2.5	48.3	20	27.5			Maktabi and others (2013)
Italy	660	11.8		24.8	14.2				Vegara and others (2014)
Island of Ireland	100	23	16		15			17	Anon (2015)
Nigeria	180	25 to 80[a]		20 to 75[a]					Oluwafemi and others (2015)

[a]depending on region.

refrigerators for longer than the recommended 2 d after opening. In addition, although 32% had not been stored beyond the recommended time, it was reported that they would be stored beyond the recommended time with the intention of consuming them eventually (Evans and Redmond 2015). In the U.S., it has been reported that 4% of consumers may store cheeses for more than 45 d (Pouillot and others 2010). There is also anecdotal evidence that some householders in the U.K. store dairy products (including at-risk cheeses) in the door of their refrigerator (which is often the warmest position in a refrigerator) (Table 9).

When asked, 18% of Swedish householders stated that they would not eat food beyond the "best-before" date, whereas 70% said that they first smell and taste the food before discarding it (Marklinder and others 2004). The remaining respondents said that it depended on the type of food. In comparison, when considering the "use-by" date, 46% of the respondents answered that they would not consume a food product after the "use-by" date, whereas 30% would first smell and taste the food before discarding it. A survey in the island of Ireland reported that 75% of participants reporting never consuming fresh meat and fish, cooked meats, milk, and coleslaw after the date on the label (Anon 2015a). Around 20% of participants reported that sometimes, they consumed other foods including fruit, vegetables, salads, convenience foods (including pasta sauce), cheese, yogurt, and ready meals after the date on the label.

Energy Consumption and Waste

While, as this review shows, the temperature performance of domestic refrigerators does not appear to have improved significantly in the last 30 y, the energy efficiencies of refrigerators have improved. This is important as refrigerators have a significant environmental impact. As we highlighted in a previous review on the impact of climate change on the food cold chain (James and James 2010), in a life cycle study of ketchup, Anderson and others (1998) found that the energy used in long-term storage in home refrigerators can dwarf energy use in any other part of the ketchup life cycle by a factor of 2 or more on a per kilogram basis (as an aside, interestingly, the fuel used for consumer shopping can be as much as the fuel used in all other transportation earlier in the ketchup life cycle).

Energy labeling of domestic refrigerators, combined with minimum requirements, has led to a reduction of 26% in energy consumption per refrigerator in 10 y in the U.K. (Heap 2001; DTI 2002). According to Carlsson-Kanyama and Faist (2000), a 10-y-old refrigerator uses approximately 2.7 times as much energy per liter of usable volume as a new A-class one. Refrigerator design areas with a potential to improve the energy efficiency of refrigerators have been reviewed recently by Belman-Flores and others (2015).

Numerous factors have been found to affect the energy consumption of individual refrigerators. These include room temperature, position close to sources of heat, frequency of door opening, and thermostat setting (ranked in order of importance according to Saidur and others 2002, 2008 and Geppert and Stamminger 2013). These factors are, of course, also important with respect to temperature control. Few studies have addressed the effect of thermostat setting on energy consumption beyond acknowledging that reducing the thermostat setting will increase energy consumption. The energy consumption of fridge-freezers is complicated by the fact that in most models, a single thermostat, sited in the refrigerator section, is used to control both the refrigerator and the freezer temperatures (Brown and others 2014). Adjusting this thermostat therefore affects not only the refrigerator temperature but also the freezer temperature, compounding the effect of temperature setting on energy consumption. Saidur and others (2002) found that energy consumption in a fridge-freezer increased by about 7.8% for every degree reduction in operating temperature. Brown and others (2014) calculated that lowering refrigerator air temperatures from a mean of 7 to 4 °C would result in an annual energy consumption increase of approximately 14.1 to 36.8 kWh per refrigerator (depending on the type of refrigerator).

The development of "smart home" automation technologies (such as smart refrigerators) may enable energy demand to be shifted over time in order to better match demand with output of generation capacities, so-called "demand side management" (DSM). Flexible demand would allow better integration with systems with variable generation capacities such as those from renewable energy sources like wind power. This could be coupled with "ice bank" refrigerators such as those designed by The Sure Chill Company, which build up a bank of ice when power is available that provides cooling when there is no direct power (Lynch 2014). The energy-saving benefits of DSM have to be balanced with the needs to ensure that temperature control and food safety are not compromised (Gottwalt and others 2011; Zehir and Bagriyanik 2012; Niro and others 2013; Belman-Flores and others 2015). Refrigerators can be switched off for a time without negative impacts on temperature (Ovca and Jevšnik 2009b; Anon 2012; Niro and others 2013). Studies have shown that substantial savings can be made. In a recent example in the U.K. (claimed to be "Europe's largest field trial of Smart Grid home appliances"), a total of 1000 refrigerators were trialed. This work was sponsored by utility supplier Npower, in collaboration with appliance manufacturer Indesit and smart grid specialists RLtec (now Open Energi). A simple component was added alongside the refrigerator thermostat that delayed the compressor switching on or off in response to grid line frequency. Carbon savings of approximately 1 metric ton of CO_2 per refrigerator lifetime were attributed to each pilot refrigerator (Anon 2012). A Turkish study showed that 37.9% of a refrigerator's demand in a peak period could be shifted to other periods, and annual electricity bills for customers could be reduced by 11.4% (Zehir and Bagriyanik 2012).

A Mexican study (Arroyo-Cabañas and others 2009) calculated that totally replacing all older refrigerators with newer more energy-efficient models would save Mexico 4.7 TWh per year, the equivalent of 33% of their annual consumption of electric power. However, considerable energy is needed to manufacture a new domestic refrigerator, which could lead to an increase in CO_2 emissions in the short term. Also, although replacing older models of refrigerators may be beneficial to society from an energy consumption and environmental perspective, it may be uneconomical for householders. A life cycle analysis study to determine the optimal refrigerator replacement policy in terms of energy, greenhouse gas emissions, and cost by Kim and others (2006) showed that optimal lifetimes range from 2 to 7 y from an energy objective, and 2 to 11 y from a global-warming potential (GWP) objective; however, an 18-y lifetime minimizes the economic cost to the owner. These environmental benefits assume that older refrigerators are scrapped. This is not always the case. For example, a Canadian study (Young 2008) found that many households continue to use their old refrigerators after the purchase of a new one, such old refrigerators often being referred to as a "beer fridge." Similarly, a Norwegian study (Strandbakken 2009) found that between 62% and 74% of "replaced" refrigerators were disposed of in a way that prolonged their working life.

As mentioned in our previous review (James and James, 2010), some researchers (Estrada-Flores 2008) have pointed out that the need for more energy-efficient domestic appliances will need to be balanced with the fact that in the future, food products will become more expensive and therefore more valuable. Thus, it is likely that householders in the future will demand that domestic refrigerators maximize product shelf-life. This would require lower refrigerator temperatures than at present, which could increase energy consumption. However, any increase in energy consumption is likely to be offset by a reduction in food waste. Van Garde and Woodburne (1987) found that when household refrigerator temperature increased from 2 to 20 °C, the amount of discards also increased proportionally. Brown and others (2014) calculated that reducing mean refrigerator temperatures from 7 to 4 °C could save the U.K. £162.9 million of waste annually, with a reduction of associated emissions of 270,000 metric tons of CO_2. Including certain foods that are not always refrigerated and removing others that do not benefit from refrigeration, the estimated savings increased to £283.8 million and 578,383 metric tons of CO_2. Based on an experimental assessment, the costs and emissions associated with increased refrigerator energy consumption were considerably lower at £80.9 million and 367,411 metric tons of CO_2.

Advanced Features in Refrigerators

While this review shows that storage temperatures, householder use, and the performance of refrigerators appear to have not changed in many years, it cannot be said that refrigerator manufacturers have been oblivious to change. Manufacturers have introduced many novel advanced features to their refrigerators: to improve temperatures and the storage life and quality of foods.

Market studies in the U.K. (Mintel 2016) show that the main reasons households purchase a new refrigerator is to replace a broken or unreliable one (45%), buy a bigger refrigerator (17%), or as a first-time purchase (11%). Only 8% of purchases are because of new features or to save energy. However, energy consumption is considered important when purchasing a new refrigerator. A Mintel report in 2013 indicated that over 3 quarters (79%) of respondents considered energy efficiency as the most important factor influencing the purchase of a refrigerator (or freezer), with 50% of respondents considering this factor as important and 29% considering it very important (Mintel 2013).

When asked about what advanced features they would be interested in, according to Mintel (2016), 25% of U.K. respondents reported that they would pay more for a refrigerator with "technology that keeps food fresher for longer" (Figure 1). While 21% of respondents would consider paying more for refrigerators with antibacterial linings/coatings, and 16% to 17% would pay more for odor control technology and freshness monitors. Most refrigerator manufacturers offer models of refrigerator with 1 or more of these advanced features.

Antibacterial linings, incorporating triclosan and various forms of silver, have been used in commercially available refrigerators (Kampmann and others 2008; Møretrø and Langsrud 2011). Such technologies are usually marketed as beneficial for improving the storage life of food and reducing waste. Both Ilg and others (2011) and Kampmann and others (2008) have evaluated the potential effectiveness of surfaces containing silver in domestic refrigerators under laboratory conditions. Both studies found that materials containing silver could reduce inoculated bacteria (*Pseudomonas fluorescens, Lactobacillus delbrueckii,* and *S. aureus*) by between 1.0 to 5.9 and 0.1 to 7.4 $\log_{10}$ CFU/mL, respectively, compared with the

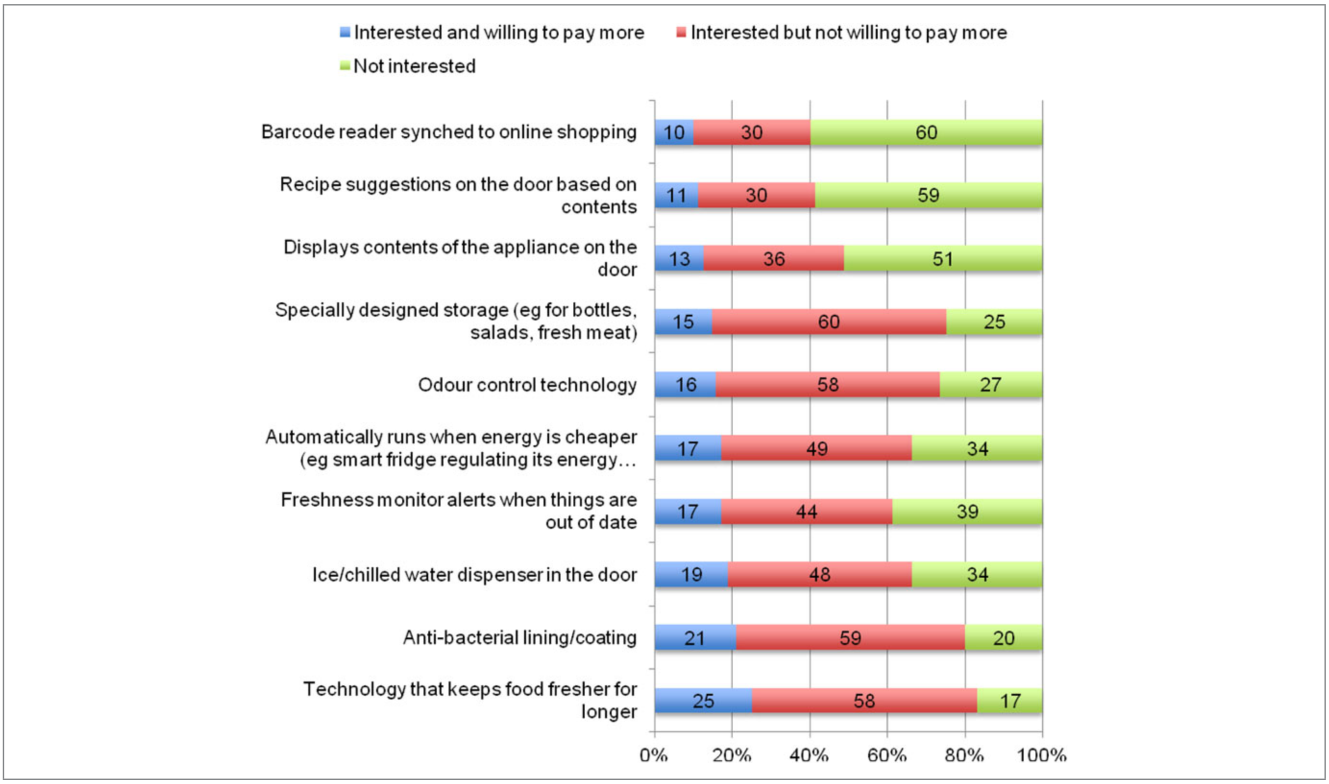

Figure 1–Consumers interest in advanced features in refrigerators (data from Mintel 2016).

reference surfaces. The effectiveness was influenced by the plastic type (better in ASA (acrylic-styrene-acrylonitrile) than ABS (acrylonitrile butadiene styrene) or HIPS (high impact polystyrene)), the microorganism (more effective against *P. fluorescens* than *L. delbrueckii or S. aureus*), and temperature (less effective at 5 °C than 35 °C). While Kampmann and others (2008) reported that the inhibitory effect of silver compounds was not suppressed by the presence of protein residues, Ilg and others (2011) reported the opposite to be the case. "AlphaSan" was used in refrigerators by Bosch and Siemens Hausgeräte GmbH and evaluated by Kampmann and others (2008). Some Samsung refrigerators (Samsung 2005) also incorporate silver nanocoatings (so-called "Silver Nano^{TM} Health system").

A laboratory evaluation of the effectiveness of ionizers in domestic refrigerators to reduce airborne and surface bacteria was carried out by Kampmann and others (2009). The ionizer produced both ions (1.2 to 3.7 × 10^6 ions cm^{-2}) and ozone (10 to 45 ppb). The constructional layout and material properties of the ionizer housing, air circulation within the refrigerator, and the interior volume were found to affect the effectiveness. Reductions of 0.7 to 2.5 $\log_{10}$ CFU were reported, with Gram-positive bacteria being more resistant than Gram-negative bacteria. Ionizers appear to have been widely adopted by a number of refrigerator manufacturers, for example, Gorenje "IonAir" (Anon 2015b; Gorenje 2016), Toshiba Hybrid Plasma (Anon 2015b), and Sharp "Plasmacluster" (Anon 2015b; Sharp 2016). Hotpoint has embraced ozonation with its "Active Oxygen" technology (Anon 2015b; Hotpoint 2016).

Air filtration systems, to eliminate odors and reduce airborne microorganisms, have been introduced by many manufacturers, such as Electrolux "TasteGuard" (Electrolux 2016), LG "HygieneFresh" (LG 2016), Whirlpool Microban (triclosan) (Anon 2016), Panasonic "HygieneAir" (Panasonic 2013), and Bosch "AirFresh Filter" (Bosch 2016).

Beko and Blomberg have introduced "blue light" light-emitting diodes (LEDs) lighting to the salad drawer of some of their refrigerators (Beko 2016; Blomberg 2016). This "blue light" technology is claimed to allow fruits and vegetables to continue to photosynthesize thus prolonging storage life and even increasing vitamin C content. The application of LED lighting in food applications was recently reviewed by D'Souza and others (2015). A few studies (such as Braidot and others 2014; Lee and others 2014) have investigated the effects of illumination from different LED lighting colors during the refrigerated storage of fruits and vegetables. There is evidence that different colors have different effects, blue possibly having a greater effect on vitamin C production than other colors (Lee and others 2014). LED lighting has also been shown to have an antibacterial effect (D'Souza and others 2015; Ghate and others 2015).

Most, if not all, refrigerator manufacturers market refrigerator models that have "chill compartments." According to IEC 62552:2007 (Table 1), these compartments are "intended specifically for the storage of highly perishable foodstuffs" and should operate at temperatures between −2 and +3 °C. As discussed above, since 2002, in France, all refrigerators must have chill compartments. This is currently not the case in other countries; certainly, there are many refrigerator models on sale in the U. K. that do not have chill compartments. Very few published studies appear to have looked at the performance of these compartments, and none on the performance of refrigerators in homes. Fukuyo and others (2003) demonstrated that rapid cooling and improved thermal uniformity could be achieved in refrigerators by improving the airflow through the addition of fans and jet slots. Sun and others (2005) evaluated such compartments for the storage of steak, minced beef patties, and salmon, as well as a refrigerator with an "ultrachilled" compartment (running at a mean air temperature of −4.8 °C, and a standard deviation of 1.0 °C). Not all of the 5 models of refrigerator evaluated had independently controlled temperature compartments, and, unfortunately, it is difficult to identify from the author's descriptions which did and which did not. Consumer preference tests indicated that panelists preferred the samples stored under or near ultrachilled conditions (mean air temperatures of −4.8 or −2.0 °C, respectively) rather than samples stored under the 3 more standard refrigerated conditions evaluated (mean air temperatures of −0.1, 1.5, or 1.7 °C). It was reported that steak, mince, and salmon were acceptable (microbially) for 8, 8, and 4 d, respectively, in the refrigerators operating at −2.0, −0.1, 1.5, or 1.7 °C. While the shelf-life of all of the foods was extended to 10 d in the refrigerator operating at −4.8 °C. It is unclear whether the meat held at this temperature was superchilled (partially frozen) or supercooled (still in an unfrozen state). Mitsubishi Electric Corp, Tokyo, Japan (Sato and Monozukuri 2014) have marketed refrigerators with supercooled compartments (−3 to 0 °C) in which the food is claimed to be held in a supercooled state (at a temperature below its freezing point without ice nucleation taking place).

The idea of connecting home appliances to the Internet (the Internet of Things) has been mooted since the late 1990s. Refrigerators have long been seen as one of the home appliances that would benefit from this. Possibly the first prototype "smart" refrigerator was demonstrated by V Sync in 1998 (Kuniavsky 2010). Launched in June 2000, LG Electronics Inc. "Internet Digital DIOS" was probably the world's first internet "smart" refrigerator to reach the market (Wilkenfeld and Harrington 2015). However, so far, smart refrigerators have had a little impact, reasons for this have been discussed by numerous authors (such as Luo and others 2009; Kuniavsky 2010; Alolayan 2014; Arthur 2014; Cook 2016; Wilkenfeld and Harrington 2015). Mintel (2014) reported in 2014 that over a third (34%) of U.K. refrigerator shoppers expect to, or would pay, more for a barcode reader synchronized to online shopping. They also reported that surveys had shown that nearly 1 in 5 (18%) of U.S. consumers would be interested in a refrigerator with a built-in computer to keep an inventory of products. We are unaware of any scientific studies that have independently evaluated the potential benefits of Internet-enabled, so-called "smart" refrigerators in comparison with conventional refrigerators.

While refrigerators with some of these technologies and features have been available for a number of years, there appears to be no evidence of them having an impact on recent surveys of refrigerator temperatures and use. This is probably because these features are only available in more expensive refrigerators, and thus represent a small subset of current household refrigerators. We are unaware of any independent studies that have evaluated the impact of these technologies under true domestic conditions.

Conclusions

Arguably, the modern chilled food cold chain would not be possible without the domestic refrigerator. While taken for granted in the developed world, ownership of refrigerators, although growing, is still low in many developing nations.

Since our review of refrigerator performance in 2008 (James and others 2008), further surveys have been carried out around the world on the domestic storage of chilled foods. These studies, in general, continue to show remarkable similarities in householder attitudes, handling of chilled foods, and the performance of refrigerators around the world. It is still the case that, despite numerous recommendations on handling and storage temperatures, householder use and the performance of refrigerators appear to have remained remarkably unchanged throughout the world over the last 30 or so years. Many householders still do not follow recommended advice on the storage of chilled foods, fail to know or monitor the temperature of their refrigerator, and are storing chilled foods at higher-than-recommended temperatures. It is usually recommended that a refrigerator should operate between 0 and 5 °C. However, as this review shows, the overall weighted arithmetic mean of mean temperatures measured throughout the world is about 6.1 °C. Consequently, over 50% of refrigerators operate at a mean temperature above this.

While advanced features, such as temperature-controlled drawers, antimicrobial coatings, ionizers, and so on, have been developed by refrigerator manufacturers and are available in some models, these technologies do not appear to have yet had an impact on the measured temperature performance or cleanliness of household refrigerators.

How refrigerator temperatures and cleanliness affect consumer health still remains to be fully assessed. In general, studies would suggest that refrigerators themselves are not a significant vector in the transmission of food-poisoning microorganisms. However, it is clear that the temperatures in many refrigerators throughout the world will support the growth of food pathogens on foods during storage.

While temperature performance may not have improved in the last 30 y, the energy efficiency of refrigerators has improved. Much of this improvement can be credited to the introduction of clean energy labeling.

Most refrigerators still come without any temperature display. Although many authorities recommend the use of refrigerator thermometers, few households appear to regularly monitor the temperature of their refrigerator. There is clearly a need for refrigerators to be fitted with thermometers and displays that clearly show the householder the operating temperature of their refrigerator. Without the ability to monitor the internal temperature, it is unsurprising that the temperatures in many refrigerators are higher than recommended. However, this is not a new conclusion, one of the earliest papers on the performance of refrigerators that we know of, by Broadhurst and van Arsdale (1924), closes with the following recommendation that "thermometers should be supplied for the warmest and coldest shelves at least." Despite the reduction in the cost of sensor technology in recent years, the majority of the refrigerators on the market throughout the world still do not have built-in sensors that show householders what the temperature of their refrigerator is.

Author Contributions

C. James compiled information from the literature, analyzed the data, and wrote parts of the manuscript; B. Daramola contributed to analyzing the data on the microbiological aspects and also wrote parts of the manuscript; S. J. James contributed to the analysis of the data, writing of the manuscript, and to editing the paper for submission.

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