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Research Article

Meat microbiota: A conceptual review

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Abstract

Changing life style and food habit increase concern about meat and meat products serving as vehicles of food-borne cluster of micro-organisms. Major and highly publicized outbreaks of food-borne disease have been associated with consumption of contaminated meat and have led to increased interest in meat safety among public health agencies, regulatory authorities, researchers, industry and consumers. Thus, authorities in most developed countries have established regulatory requirements aimed at improving the hygienic status of the meat supply. Characteristics of meats, types and sources of microbiota, the main factors governing microbial proliferation and their detrimental effects, prevention measures to spoilage meat and meat products, and finally the reference values for different counting methods are needed to establish regulatory initiatives. Thus, the present review will discuss each and every point of the above.

Introduction

Meat is a relatively concentrated source of high-quality protein that is readily digestible compared with many plant foods. A wide range of micro-organisms from different sources are introduced onto moist muscle surfaces that are rich in nutrients. The composition and abundance of microbiota absolutely depends on animal health, dressing skills, personnel hygiene, abattoir cleanliness, and adequate storage and holding temperature during distribution and retail. Moreover, the ability to utilize available nutrients in the muscle through assimilation or proteolysis of complex molecules into readily utilizable substrates is another option for the survival and proliferation of micro-organisms deposited on meat surfaces. The micro-organisms can be classified into pathogenic micro-organisms and spoilage microorganisms (Narashima et al., 1998). Meat and meat products can be spoiled as a result of large numbers of spoilage bacteria such as *Pseudomonas* spp. or Brochothrix thermosphacta which cause the formation of slime, gas, discoloration and an off-flavor but no toxin. Pathogens are able to produce one of two different types of toxin which can be harmful to humans. Food poisoning can occur in the form of a food infection on one hand or intoxication on the other. In both cases, growth in the number of bacteria has to take place, either within the human being (infection) or within food itself (intoxication) to generate sufficient toxin to cause illness. Gram-negative bacteria generally produce endotoxins which are lipo polysaccharides and which cause food infections. Pathogens consumed place them mainly in the gastrointestinal system and growth takes place there. Exotoxins are primarily proteins and enzymes and are produced inside the bacteria through metabolic activity. They cause intoxication in meat and meat products. Exotoxins are primarily produced by Gram-positive bacteria and are not part of the cell wall but are proteins synthesized as a result of metabolic activity. They are released into the environment surrounding the cell such as meat or meat products. Exotoxins are soluble in body fluids and can therefore be easily transported all over the body, partly destroying the host cell by interfering with its metabolism. Three different types of toxin belong to the group of exotoxins: cytotoxins, enterotoxins and neurotoxins. Neurotoxins interfere with the nervous system whilst enterotoxins affect the lining of the intestines and cytotoxins even kill the host cells. Exotoxins are produced by bacteria while they grow in numbers, are released into the food and cause food intoxication. Contaminated, or poisoned, food has to be consumed in order to fall sick. Intoxication is also occasionally known as food poisoning as the poison is already present in food consumed; however, both infection and intoxication ultimately result in food poisoning. As the toxins are already present in consumed food, the incubation time for intoxication is short and sickness can be seen around 3– 4 h after the contaminated food was eaten. Vomiting and diarrhoea, as well as headache and stomach ache, are the main symptoms.

Properties of meat

Meat referred as a complete protein because they provide all nine essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine). Meat is a relatively concentrated source of high-quality protein that is highly digestible compared with many plant foods. Slaughter of food animal is followed by a series of physical and chemical changes over a period of several hours or even days resulting in the conversion of muscle to meat (Smulders et al., 2014). At the time of death, the muscle is flaccid and highly extensible due to

having 1.5 µmol ATP in per g muscle. This ATP drops (1 µmol/g muscle or less) within a few hours (1-2, 2-4, 4-8 in broiler, sheep and goat, and cattle, respectively) and makes the muscle being inextensible and relatively rigid, a phenomenon known as rigor mortis (Etherington et al., 1987). The completion of rigor ends within 2–4 hours, 12–16 hours, and 24–36 hours in broiler, sheep and goat, and cattle, respectively (Greaser, 2001). A state refers as 'conditioning' develops which results lower in pH levels, water-holding capacity, less tender and color muscle while continuing rigor. But, those changes come back normal through proteolysis when meat keeps under @ 2°C up to 4-7 days as known as 'aging or chilling' and this is required to provide high-quality protein enriched meat to the consumers (Gerhard, 2016). Abundant levels of lactic acid formation during post mortem glycolysis is responsible for the decline in pH value and water-holding capacity, resulting in proliferating micro-organisms and changes in color within the meat (Warriss, 2000).

The micro-organisms of primary concern in raw, processed and packaged meats

The slaughtering and butchering of food animals provide a wide range of micro-organisms introduced to meat surfaces as it contains abundant nutrients and water. It is argued that only a small portion (10%) of these microorganisms is capable of survival and proliferation during storage, distribution, and retail sales of meats (Remenant et al., 2015). Additionally, an even a smaller portion will eventually predominate and cause spoilage. The micro-organisms can be classified into pathogenic micro-organisms and spoilage microorganisms (Narashima et al., 1998). The major groups of pathogenic micro-organisms (Table 1) associated with meat and meat products are Salmonella, Staphylococcus, Escherischia coli, Listeria monocytogenes, Bacillus cereus, Clostridium botulinum, Clostridium perfringens, Yersinia Enterocolitica, Campylobacter spp. and Aspergillus flaws. The micro-organisms that contribute to the spoilage (Table 2) of meat and meat products are Pseudomonas, Micrococcus, Lactic acid bacteria, Brochothrix thermosphacta, Acinetobacter, Moraxella, Enterobacteriaceae, Shewanella putrefaciens, Aspergillus, Penicillium, Thamnidium, Rhizopus, Cladosporium, Sporotrichum, Debaryomyces, Candida, Torulopsis and Rhodotorula.

Table 1. Major genera of pathogenic microbiota commonly found on meats

	Type of meat		
Gram-positive bacteria	**Raw**	**Processed**	**Vacuum packaged**
Enterococcus	✓	✓	✓
Staphylococcus	✓	✓	✓
Micrococcus	✓	✓	✓
Pediococcus	✓	✓	✓
Lactobacillus	✓	✓	✓
Brochothrix	✓	✓	✓
Corynebacterium	✓	✓	✓
Microbacterium	✓	✓	✓
Kocuria	✓	✓	✓
Leuconostoc	✓	✓	✓
Weissella	✓	✓	✓
Bacillus	✓	✓	
Paenibacillus	✓	✓	
Listeria	✓	✓	
Carnobacterium	✓		
Clostridium	✓		
Kurthia	✓		
Lactococcus	✓		

Table 2. Major genera of spoilage microbiota commonly found on meats

	Type of meat		
Gram-negative bacteria	**Raw**	**Processed**	**Vacuum packaged**
Acinetobacter	✓	✓	✓
Enterobacter	✓	✓	✓
Aeromonas	✓	✓	✓
Serratia	✓	✓	✓
Providencia	✓	✓	✓
Pseudomonas	✓	✓	
Alteromonas	✓	✓	
Hafnia	✓	✓	
Shigella	✓	✓	
Achromobacter	✓		
Campylobacter	✓		
Psychrobacter	✓		
Citrobacter	✓		
Alcaligenes	✓		
Escherichia	✓		
Flavobacterium	✓		
Yersinia	✓		
Salmonella	✓		
Pantoea	✓		
Moraxella	✓		
Kluyvera	✓		
Klebsiella	✓		
Vibrio		✓	
Janthinobacterium		✓	

Source: Dillon, 1998; Garcia-Lopez et al. 1998; Jay, 1998.

Causes of microbial proliferation in fresh, processed and packaged meat

Temperature

The most important single factor governing microbial growth is temperature. Broadly, the higher the temperature the greater is the rate of growth. Jensen (1945) classifies meat spoilage organisms in three categories. Psychrophiles (psychrotrophs) have temperature optima between –2°C and 7°C, mesophiles between 10°C and 40°C and thermophiles from 43 to 66°C. Most spoilage microorganisms that are associated with meats are considered to be psychrotrophs, while most pathogenic bacteria are considered to be mesophiles. There are some strains of pathogenic bacteria, most notably Listeria monocytogenes, which are psychrotrophic and some species of Clostridium and Bacillus are considered to be thermophilic. As bacteria generally grow more rapidly than fungi and mold, spoilage of meat is thought to develop only when competing bacteria are inhibited. Temperature is usually assumed to be the critical factor; mold spoilage being typically associated with frozen meat. It has been generally accepted that molds can develop on meat at temperatures as low as -10 or -12°C. The mold growth on frozen meats is indicative of particularly poor temperature control.

pH

Most meat spoiler microflora grows better in a pH range of about 6.6–7.5. Therefore, meat at pH6.0–6.2 will spoil faster than meat at pH 5.2–5.4. The ultimate pH remains higher (>6.0) in meat of stress-exposed animals than the normal value (5.6) in a non-stressed animal due to the earlier completion of rigor mortis (Salahuddin et al., 2019). Under low pH slows the growth of bacteria grown outside their optimal pH range by slowing down the functioning of the enzyme systems and the transport of nutrients into the microbial cells. Some lactic acid bacteria, for example, Lactobacillus brevis and L. plantarum can grow at pH 3.16 and 3.34, respectively. Generally, at pH below 4.0 yeasts grow better than bacteria, whereas only molds can be found at pH values below 1.5 (Jay et al., 2005).

Water availability

The availability of free water in meat during freezing is critical for the proliferation of microbial growth. This available water is termed as water activity (*A*w) in the meat industry. In general, the higher the *A*w, the more free-water is available for microbial growth. The scale for water activity is 0.00–1.00 where pure water has an *A*w of 1.00. Generally, most spoilage bacteria cannot grow below *A*w of 0.91; however, molds can grow at *A*w as low as 0.80. With respect to food borne pathogens, S. aureus can grow at *A*w as low as 0.86. In contrast, C. botulinum does not grow below *A*w of 0.94 (Jay et al., 2005). There are also molds and yeasts that have the ability to grow where there is very low water activity. Most fresh food products have a water activity of 0.99 or greater which makes these products a good medium for microbial growth.

O_2 requirement

The growth of surface spoilage organisms on meat and meat products depends on their tolerance of, or need for, oxygen (O_2). Microorganisms are classified on the basis of the oxygen tension: obligate aerobic, facultative anaerobic, obligate anaerobic, and microaerophilic. Obligate aerobic bacteria require oxygen in order to live and to grow. Bacteria such as Pseudomonas spp. and Aeromonas spp. belong to this group as well as fungi and the absence of O_2 leads to the death of those organisms. Facultative anaerobic bacteria, such as lactic acid bacteria, can use O_2 if present but can live without oxygen as well. However, growth of lactic acid bacteria is enhanced by the presence of carbon dioxide (CO_2). Obligate anaerobic bacteria cannot tolerate O_2 which acts as a poison towards them. The most well-known representative in the group of obligate anaerobic bacteria is C. botulinum. Microaerophile organisms thrive in an atmosphere containing reduced levels, around 6% and below of O_2. Growth is stimulated by the presence ofCO_2 and a level of 10–12% is seen as the optimum. The presence of O_2 sometimes affects the required water levels of a bacterium. For example, Staph. aureus shows growth at an Aw of 0.90 under anaerobic conditions.

Nutrient Content

Compounds such as sugars (simple and complex), alcohols, and amino acids can be used by microorganisms for energy requirements. If a food is high in complex sugars, most microbes will break these down into simple sugars such as glucose before they are utilized. Some microbes are able to use fats as an energy source, but these types of microbes are not relatively high in numbers. The primary nitrogen source for microorganisms on food products is amino acids. As with sugars and other compounds that are used for energy, the microbes generally utilize the least complex compounds first with some microbes having the ability to catabolize more complex compounds into simple amino acids before use. Microbes also require vitamins, growth factors, and minerals. Many microbes are able to synthesize many of the vitamins and growth factors that are needed for growth and survival. However, most meat products have an abundance of these compounds that are available for use by the microorganisms if they cannot be synthesized.

Table 3. Characteristics of growth for food-poisoning pathogens associated with meat

	Factors affecting microbial proliferation				
Organism	**Temp (°C)**	**pH**	**O_2 req.**	***Aw***	**Mode of**
Gram +ive					
Bacillus aureus	32-45	>4.5	facultative	0.96	Intoxication
C. Botulinum	40-50	>4.7	Obligate anaerobic	0.95	Intoxication
C. perfringens	40-50	>4.9	Obligate anaerobic	0.97	Intoxication
S. aureus	35-45	>4.6	Facultative	0.90	Intoxication
L. monocytogens	0	>5.0	Facultative	0.92	Infection
Lactobacillus spp	0	>3.2	Facultative	0.93	Infection
Gram -ive					
Enterobacteriaceae (Salmonella and E coli)	5-7	4-4.4	Facultative	0.95	Infection
Campylobacter	40-45	5	microaerophilic	0.97	Infection
Y. enterocolitica	-1	4.4	Faculattive	0.92	Infection
Pseudomonas spp	35-45	4.7	aerobic	0.97	Infection
A hydrophila	0	5.3	Facultative	0.92	Infection
Leuconostoc	12	4.8	Facultative	0.93	Infection
Yeast and mold	-10-18	4.5	aerobic	0.60-80	Infection

Consequences of microbial proliferation in meats

Color defect

The color of meat, especially for red meat is the first appreciation criterion that can lead to reject the product. Some microbial species, like pseudomonas fluorescens species have the ability to produce a wide range of (blue/green/yellow) pigments. The well-known yellow fluorescent pigment is a siderophore, a molecule produced for the captation and use of iron (Cornelis, 2010). Blue pigment production leading to spoiled “blue pork” or “blue beef” was also reported, as was observed in mozzarella cheese (Andreani et al., 2014). Besides these colorations by pseudomonas strains, the greening of meat has also been occasionally reported to be due to some LAB activities on myoglobin discoloration, i.e., dihydrosulphide or hydrogen peroxide produced by bacteria leading to greening or graying meat (Borch et al., 1996).

Texture defect

A second visual defect that can affect the consumer choice is the ropy appearance of meat products. In fact, it has been reported in the past that spoiling effect of some species stood in their ability to produce ropy slime. This has been the case for some L. sakei strains in frankfurters for example (Bjorkroth and Korkeala, 1997). Slime formation was also reported in rabbit carcasses or turkey breasts (Soultos et al., 2009; Samelis et al., 2000). From a metabolic point of view this ability relies on the production of polysaccharides by species, in particular from the LAB group (Notararigo et al., 2013). However, despite these reported cases in the literature, this defect is nowadays little evidenced. One must nevertheless keep in mind this ability of some strains of the meat microbiota, as this can lead to biofilm production and thus can modify interactions between the resident species, for example the pathogenic ones.

Odor and taste

The spoilage potential of microorganisms depend on their growth and also their abilities to produce metabolites from the meat substrate according to their metabolic capacities. The spoilage defect is thus often the result of several interactions between microorganisms and between molecules. Global approaches that target all these compounds are thus promising to decipher on the role of various compounds and the contribution of the diverse microorganisms. The odor is a complex association of molecules; which association can be considered as pleasant or unpleasant depending on juries. Recently, Casaburi et al. (2014) made an extensive review on the volatile organic compounds potentially produced by the spoilage associated microorganisms. The authors underline that there is a lack of descriptors for fresh uncooked meat. Alcohols, aldehydes, ketones, esters, and sulfur compounds are thus referenced throughout a literature survey in link with the odor descriptors. The base odor of fresh meat was defined with notes of fatty, cheesy, dairy or fatty, or grassy odors. Rancidodors, cabbage, and floral/citrus odors are rather presented as unpleasant.

Biogenic amine production

Biogenic amines are produced through enzymatic decarboxylation of amino acids. Whereas tyramine and histamine, issued respectively from tyrosine and histidine, are of safety matter, other biogenic amines result in food spoilage. In particular putrescine and cadaverine, toxic only in large doses, are responsible for meat spoilage because of the putrefying odor they cause. Their production during the storage of different meat products has been associated with bacterial development and depends on storage conditions, in particular on the gas atmosphere used for packaging (Balamatsia et al., 2006; Galgano et al., 2009; Li et al., 2014). In addition, in fermented sausages, the availability of free amino acids is a limiting factor for the bacterial synthesis of biogenic amines (Latorre-Moratalla et al., 2014). Therefore, biogenic amine production depends on bacteria that harbor amino acid decarboxylases and on storage conditions enabling microbial development and may vary depending on amino acids availability. This may explain the indirect effect of some bacterial species, which do not produce biogenic amines but may enhance their production by other bacteria (Nowak and Czyzowska, 2011).

Gas production

Vacuum-packed meats stored at low temperatures are susceptible to spoilage by bacteria able to survive at low temperature and in the absence of oxygen. Vacuum packaging of chilled meat has been developed to export lamb cuts for long distances and therefore requiring long shelf life. This process has been accompanied by the appearance of the so-called blow pack defect, due to gas production by bacterial metabolism. In this type of spoilage, the vacuum is lost because of CO_2 production, and may be accompanied by the production of off odors, depending on the nature of the gas that is produced and on the bacterial species

responsible for it. Enterobacteriaceae have been reported to be associated with this defect (Brightwell et al., 2007) and cold-tolerant Clostridium spp., in particular Clostridium estertheticum and Clostridium gasigenes, which can develop on meat and produce CO_2 in the packs (Mills et al., 2014; Remenant et al., 2015; Dousset et al., 2016).

Table 4. Common defects of meats and causal bacteria

Defect	Meat product	Bacteria
Slime	Meats	Pseudomonas, Lactobacillus, Enterococcus, Weissella, Brochothrix
H2O2 greening	Meats	Weisella, Leuconostoc, Enterococcus, Lactobacillus
H2S greening	Vacuum-packaged meats	Shewanella
H2S production	Cured meats	Vibrio, Enterobacteriaceae
Sulfide odor	Vacuum-packaged meats	Clostridium, Hafnia
Cabbage odor	Bacon	Providencia
Potato odor	Ham	Burkholderia, Pseudomonas
Putrefaction	Ham	Enterobacteriaceae, Proteus
Bone taint	Whole meats	Clostridium, Enterococcus
Bone taint	Bacon	Proteus, Vibrio
Pocket taint	Bacon	Vibrio, Alcaligenes, Proteus
Internal taint	Ham	Providencia
Souring	Ham	Lactic acid bacteria, Enterococcus, Micrococcus, Bacillus, Clostridium

Source: Hui, 2001

Control of spoilage of meat

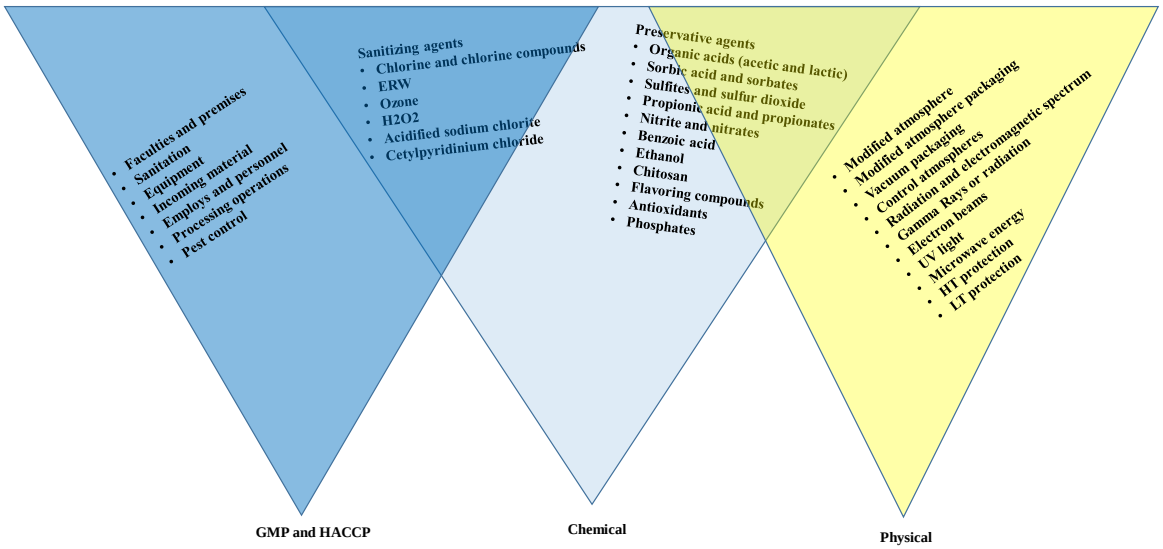

Figure 1. Control of spoilage of meats

Emerging microbe's detection method

These methods are (1) most probable number method; (2) plate count method; (3) direct microscopic counts; and (4) dye reduction methods.

Most probable number method

The most probable number, or MPN, method is widely used to determine microbial numbers in a sample. There are two types of this method that can be employed: the three-tube method, or the five-tube method. There are advantages to using this procedure that include (1) simplicity of the procedure; and (2) since MPN is a statistical test, results from multiple MPN procedures on the same sample have less included variability than comparable plate count methods. The major disadvantage of using the MPN method is the considerable use of glassware, especially for multiple samples Varying media (selective, differential, or both) can be used for the determination of specific organisms. For this procedure, appropriate dilutions of a representative sample are prepared. After preparation, three serial dilutions are placed into either 9 or 15 tubes for the three-tube method or five-tube method, respectively. After incubation in the MPN tubes at an appropriate temperature and atmospheric conditions (e.g., aerobic), the tubes are examined for growth. The count for the target organism in the original sample is then calculated using standard MPN tables.

Plate count method

This method is also one of the most widely used techniques for determining microbial presence and numbers in a sample. Although the media in which the culturing takes place can vary by the target organism, the basic technique remains the same. There are many ways to collect a sample for the plate count method. A representative sample (e.g., 25 g) can be combined with an appropriate volume of a diluents and blended or stomached to ensure homogenization of the sample. Other methods for

collecting a sample include swabs or rinses. Appropriate dilutions are made to ensure that a plate from the sample is in the standard countable range for the medium used. At this point, for some organisms, a process of enrichment may be included. This involves incubating the sample in an appropriate enrichment medium (usually broth) for a certain amount of time to make sure that any cells that may be injured are represented, or to make sure that replication of cells that may be low in numbers in the sample are represented. If a sample is subjected to enrichment, the concluding test is considered to be a presence/absence or qualitative test since the microorganisms are allowed to reproduce while in the enrichment. After the appropriate dilutions are made (or after enrichment), the dilutions are plated onto an agar medium that is suitable for the target organism. The plates are then incubated at an appropriate temperature and atmospheric conditions for the target organism. After incubation, the plates are examined and counted either by hand or by an electronic counter. For all plate count test, a selective or differential agar should be used if one is available or unless the test is for a total count of the organisms present in the sample (e.g., total aerobic count). If a selective or differential medium is not available, biochemical tests should be employed to make sure that the organism recovered is the target organism. Examples of media used for specific microorganisms include brilliant green sulfa agar (BGS) or xylose lactose tergitol 4 (XLT-4) for Salmonella spp., eosin methylene blue agar (EMB) or violet red bile agar (VRB) for enterobacteriaceae, and E. coli and modified oxford agar (MOX) for Listeria spp.

Direct microscopic count method

Direct microscopic counts consist of preparing slide smears of the sample, staining with a dye, and directly counting the number of cells on the slide. This method is not readily used by the meat industry since the main distinction that can be made is that of cell morphology. Since samples of meat products may contain morphologically similar microorganisms of different spoilage or pathogenic capacity, this method is not practical.

Dye reduction method

In the dye reduction method, an estimate of the number of microorganisms in a sample is obtained by the addition of prepared supernatants to dyes. The time that it takes to reduce the dyes is measured and a resultant estimate of the microbial population is obtained, as the time it takes for dye reduction is inversely proportional to the microbial population. For this method, either methylene blue or resazurin is used as the dye. Methylene blue changes from blue to white when it is reduced, while resazurin changes from slate blue to pink or white. The dye reduction method can be used for meats, but the presence of natural reductive substances in raw meat may pose a problem. Cooked meats do not contain the same large amounts of natural reductants as raw meats, therefore this test is applicable for these products. One solution to the presence of reductants in raw meats is to use a stomacher for homogenization of the sample rather than a blender.

Other microbial methods

There are other methods of microbial detection and enumeration that are currently available to meat producers. These include enzyme-linked immunosorbent assay (ELISA) and so-called quick tests that typically use biochemical reactions to determine microbial presence or populations. Producers are encouraged to explore all options when determining the appropriate type of microbiological test to be used in their operation. Monetary and time constraints, along with test sensitivity, tend to be the major factors in deciding which type of test to use.

Counts of bacteria in meat are in the range 102-105 cfu/cm^2 or g, but only around 10% are able to initiate growth (Nychas et al., 1988). When numbers exceed log7 cells per cm^2, the first spoilage signs are detected, as off-odors. Another typical spoilage sign, bacterial slime, is noticeable with cell density around log cells per cm^2 (Gill, 1982).

		Log10 CFU/g	
Microbial indicators	**Good**	**Critical**	**Not acceptable**
TVC	<4	4-5	>5
APC	<4	4-5	>5
TCC	<2	2-3	>3
TYMC	<2	2-4	>6
Enterobacteriaceae	<4	4-5	>5
E. coli	Absent in 25 g		
Enterococci	<2	2-3	>3
Salmonella	Absent in 25 g		
C. perfringens	absent	Absent	absent
Listeria spp.			
LAB	<3	5-6	>7
S. aureus	<2	2-3	>4
Minced meat			
Salmonella	absent		
E Coli	50		
S aureus	100		
Meat preparation			
Salmonella	absent		
E coli	500		
S aureus	500		

Conclusions

The microorganism presence on meat surfaces can induce infection and intoxication, both later results in food-poisoning. To know the accurate levels of each microbial detection methods could give the pre-assumption and take necessary steps to control any further deterioration.

References

Andreani NA, Carraro L, Martino ME, Fondi M, Fasolato L, Miotto G, Magro M, Vianello F, Cardazzo B. 2015. A genomic and transcriptomic approach to investigate the blue pigment phenotype in Pseudomonas fluorescens. International Journal of Food Microbiology, 213: 88-98.

Andreani NA, Martino ME, Fasolato L, Carraro L, Montemurro F, Mioni R, Bordin P, Cardazzo B. 2014. Tracking the blue: a MLST approach to characterise the Pseudomonas fluorescens group. Food Microbiology, 39: 116-126.

Andreevskaya M, Johansson P, Laine P, Smolander OP, Sonck M, Rahkila R, Ja¨a¨skela¨inen E, Paulin L, Auvinen P, Bjo¨rkroth J. 2015. Genome sequence and transcriptome analysis of meat-spoilage-associated lactic acid bacterium Lactococcuspiscium MKFS47. Applied and Environmental Microbiology, 81: 3800-3811.

Aznar R, Lo´pez P, Prieto A. 2013. Comparative analysis of production and purification of homo- and hetero-polysaccharides produced by lactic acid bacteria. Carbohydrate Polymers, 93: 57-64.

Balamatsia CC, Paleologos EK, Kontominas MG, Savvaidis IN. 2006. Correlation between microbial flora, sensory changes and biogenic amines formation in fresh chicken meat stored aerobically or under modified atmosphere packaging at 4 degrees C: possible role of biogenic amines as spoilage indicators. Antonie Van Leeuwenhoek, 89: 9-17.

Bjo¨rkroth J, Korkeala H. 1997. Ropy slime-producing Lactobacillus sake strains possess a strong competitive ability against a commercial bio-preservative. International Journal of Food Microbiology, 38: 117-123.

Borch E, Kant-Muemans ML, Blixt Y. 1996. Bacterial spoilage of meat products and cured meats. International Journal of Food Microbiology, 33: 103-120.

Brightwell G, Clemens R, Urlich S, Boerema J. 2007. Possible involvement of psychrotolerant Enterobacteriaceae in blown pack spoilage of vacuum-packaged raw meats. International Journal of Food Microbiology, 119: 334-339.

Casaburi A, Piombino P, Nychas GJ, Villani F, Ercolini D. 2014. Bacterial populations and the volatilome associated to meat spoilage. Food Microbiology, 45: 83-102.

Chaillou S, Chaulot-Talmon A, Caekebeke H, Cardinal M, Christieans S, Denis C, Desmonts MH, Dousset X, Feurer C, Hamon E, Joffraud JJ, La Carbona S, Leroi F, Leroy S, Lorre S, Mace S, Pilet MF, Pre´vost H, Rivollier M, Roux D, Talon R, Zagorec M, Champomier-Verge MC. 2015. Origin and ecological selection of core and food-specific bacterial communities associated with meat and seafood spoilage. The ISME Journal, 9: 1105-1118.

Chris RK. 2013. In chapter 14 (Preventing foodborne illness). The Science of Meat Quality. A John Wiley & Sons, Inc., Publication. Pp 249-255

Cornelis P. 2010. Iron uptake and metabolism in pseudomonads. Applied Microbiology and Biotechnology, 86: 1637-1645.

Dillon VM. 1998. Yeasts and molds associated with meat and meat products. In: A. Davies and R. Board (Ed.) The Microbiology of Meat and Poultry. pp. 85–117. Blackie Academic & Professional, New York.

Doulgeraki AI, Ercolini D, Villani F, Nychas GJ. 2012. Spoilage microbiota associated to the storage of raw meat in different conditions. International Journal of Food Microbiology, 157: 130-141.

Doulgeraki AI, Paramithiotis A, Kagkli DM, Nychas GJ. 2010. Lactic acid bacteria population dynamics during minced beef storage under aerobic or modified atmosphere packaging conditions. Food Microbiology, 27: 1028-1034.

Dousset X, Jaffre E, Zagorec M. 2016. Spoilage: bacterial spoilage. In: Caballero, B., Finglas, P., Toldra´, F. (Eds.), The Encyclopedia of Food and Health, vol. 5. Academic Press, Oxford, pp. 106-112.

Fidel T. 2017. In chapter 6 (Meat microbiology and Spoilage). Lawrie's Meat Science. Woodhead Publishing is an imprint of Elsevier. The Officers' Mess Business Centre, Royston Road, Duxford, CB22 4QH, United Kingdom. Pp 201-203

Galgano F, Favati F, Bonadio M, Lorusso V, Romano P. 2009. Role of biogenic amines as index of freshness in beef meat packed with different bio-polymeric materials. Food Research International, 42: 1147-1152.

Garcia-Lopez ML, Preito M, Otero A. 1998. The physiologic attributes of Gram-negative bacteria associated with spoilage of meat and meat products. In: A. Davies and R. Board (Ed.) The Microbiology of Meat and Poultry. pp. 1–34. Blackie Academic & Professional, New York.

Gribble A, Mills J, Brightwell G. 2014. The spoilage characteristics of Brochothrix thermosphacta and two psychrotolerant Enterobacteriaceae in vacuum packed lamb and the comparison between high and low pH cuts. Meat Science, 97: 83-92.

Jay JM, Loessner MJ, Golden DA. 2005. Modern Food Microbiology. 7 th ed. New York: Springer Science and Business Media, New York,USA.

Jay JM. 1998. Modern Food Microbiology (5th Ed.). Aspen Publishers, Gaithersburg, MD.

Jensen LB. 1945. Microbiology of Meats, 2nd ed., Garrard Press, Champaign, Ill.

Johansson P, Paulin L, Sa¨de E, Salovuori N, Alatalo ER, Bjo¨rkroth KJ, Auvinen P. 2011. Genome sequence of a food spoilage lactic acid bacterium, Leuconostocgasicomitatum LMG 18811T, in association with specific spoilage reactions. Applied and Environmental Microbiology, 77: 4344-4351.

Jones RJ, Wiklund E, Zagorec M, Tagg JR. 2010. Evaluation of stored lamb bio-preserved using a three-strain cocktail of Lactobacillus sakei. Meat Science, 86: 955-959.

Kabisch J, Erl-Ho¨ning C, Wenning M, Bo¨hnlein C, Gareis M, Pichner R. 2016. Spoilage of vacuum-packed beef by the yeast Kazachstaniapsychrophila. Food Microbiology, 53: 15-23.

Kabisch J, Ho¨ning C, Bo¨hnlein C, Pichner R, Gareis M, Wenning M. 2013. Kazachstaniapsychrophila sp. nov., a novel psychrophilic yeast isolated from vacuum-packed beef. Antonie Van Leeuwenhoek, 104: 925-931.

Koort J, Murros A, Coenye T, Eerola S, Vandamme P, Sukura A, Bjo¨rkroth J. 2005. Lactobacillus oligofermentans sp. nov., associated with spoilage of modified-atmosphere packaged poultry products. Applied and Environmental Microbiology, 71: 4400-4406.

Latorre-Moratalla ML, Bover-Cid S, Bosch-Fuste J, Veciana-Nogue MT, Vidal-Carou MC. 2014. Amino acid availability as an influential factor on the biogenic amine formation in dry fermented sausages. Food Control, 36: 76-81.

Li M, Tian L, Zhao G, Zhang Q, Gao X, Huang X, Sun L. 2014. Formation of biogenic amines and growth of spoilage-related microorganisms in pork stored under different packaging conditions applying PCA. Meat Science, 96: 843-848.

Liu YJ, Xie Y, Zhao LJ, Qian YF, Zhao Y, Liu X. 2015. Biofilm formation characteristics of Pseudomonas lundensis isolated from meat. Journal of Food Science, 80: 2904-2910.

Lowry PD, Gill CO. 1984. Temperature and water activity minima for growth of spoilage moulds from meat. Journal of Applied Bacteriology, 56: 193-199.

Lucquin I, Zagorec M, Champomier-Verge M, Chaillou S. 2012. Fingerprint of lactic acid bacteria population in beef carpaccio is influenced by storage process and seasonal changes. Food Microbiology, 29: 187-196.

Lyhs U, Bjo¨rkroth JK. 2008. Lactobacillus sakei/curvatus is the prevailing lactic acid bacterium group in spoiled maatjes herring. Food Microbiology, 25: 529-533.

Mills J, Donnison A, Brightwell G. 2014. Factors affecting microbial spoilage and shelf-life of chilled vacuum-packed lamb transported to distant markets: a review. Meat Science, 98: 71-80.

Nagy E, Dlauchy D, Medeiros AO, Pe´ter G, Rosa CA. 2014. Yarrowiaporcina sp. nov. and Yarrowiabubulaf.a. sp. nov., two yeast species from meat and river sediment. Antonie Van Leeuwenhoek, 105: 697-707.

Nielsen DS, Jacobsen T, Jespersen L, Koch AG, Arneborg N. 2008. Occurrence and growth of yeasts in processed meat products e implications for potential spoilage. Meat Science, 80: 919-926.
Notararigo S, Na´cher-Va´zquez M, Ibarburu L, Werning ML, De Palencia PF, Duen˜as MT, Aznar R, Lo´pez P, Prieto A. 2013. Comparative analysis of production and purification of homo- and hetero-polysaccharides produced by lactic acid bacteria. Carbohydrate Polymers, 93: 57-64.
Nowak A, Czyzowska A. 2011. In vitro synthesis of biogenic amines by Brochothrix thermosphacta isolates from meat and meat products and the influence of other microorganisms. Meat Science. 88: 571-574.
Nychas GJ, Skandamis PN, Tassou CC, Koutsoumanis KP. 2008. Meat spoilage during distribution. Meat Science, 78: 77-89.
Pothakos V, Devlieghere F, Villani F, Bjo¨rkroth JK, Ercolini D. 2015. Lactic acid bacteria and their controversial role in fresh meat spoilage. Meat Science, 109: 66-74.
Ranken MD. 2000. In chapter 5 (Microbiology). Handbook of meat product technology. Blackwell Science Ltd. MA 02148 5018, USA. Pp- 80-91
Remenant B, Jaffre E, Dousset X, Pilet MF, Zagorec M. 2015. Bacterial spoilers of food: behavior, fitness and functional properties. Food Microbiology, 45: 45-53.
Sakala RM, Kato Y, Hayashidani H, Murakami M, Kaneuchi C, Ogawa M. 2002. Lactobacillus fuchuensis sp. nov., isolated from vacuum-packaged refrigerated beef. International Journal of Systematic and Evolutionary Microbiology, 52: 1151-1154.
Salahuddin M, Azad MAK, Das SK, Hossain MM, Hasan MN, Hiramatsu K. 2019. Effect of post-transportation grazing on the physiological condition and meat quality of Black Bengal traits. Animal Science Journal, 90: 264-270.
Soultos N, Tzikas Z, Christaki E, Papageorgiou K, Steris V. 2009. The effect of dietary oregano essential oil on microbial growth of rabbit carcasses during refrigerated storage. Meat Science, 81: 474-478.
Narashima DR, Nair KKS, Sakhare PZ. 1998. Meat microbiology and spoilage in tropical countries. Chapter 7, Book (The Microbiology of Meat and Poultry). Pp-206-250.