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The Role of Aquaporin in Stress Physiology: A Review

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ABSTRACT

The concept of water movement across cell membranes eventually lead to identification of water channels, known as 'Aquaporins'. The transport function exerted by aquaporins (AQPs) is carried out efficiently by 13 distinct isoforms of AQPs in mammals. AQPs help in regulation of physiological functions of various organ systems and have a functional role in stress associated with various pathological conditions. This review summarises the involvement of AQPs in transport of ROS and oxidative stress regulation in various organ systems. AQP1, AQP4, AQP7 and AQP9 are the major AQPs in the cardiac tissues of various animals, playing vital role in the patho-physiology of congestive heart failure, myocardial oedema, myocardial ischemia and polymicrobial sepsis. In digestive system, AQP1, AQP3, AQP4, AQP7, AQP8, AQP10 and AQP11 are localised in gastro-intestinal tract, modulating patho-physiology of pseudomembranous colitis, bile induced diarrhoea, irritable bowel syndrome and intestinal ulcers. AQPs in enteric tissues are engaged in metabolism of H_2O_2, providing a protective mechanism against oxidative stress. AQP1, AQP2, AQP3, AQP4 and AQP11 are major renal AQPs involved in ureteral obstruction, nephrogenic diabetes insipidus and kidney injury. In respiratory system, AQP1, AQP2, AQP4 and AQP5 are expressed in various pathological circumstances like lung injury and pulmonary inflammation due to oxidative stress. Thus, the evidences regarding the role of AQPs in oxidative stress offer a foundation for comprehending the adaptive mechanisms to oxidative injury at cellular level, which helps in strategizing breeding programmes and serves as biomarkers for efficient diagnosis.

Key words: Aquaporins, Organ systems, Oxidative stress, ROS, Water channels.

The water molecules that transport in and out of the cells are a fundamental component of any physiological process to maintain life. This movement of water helps in the regulation of cell activity, functioning of organ systems and maintaining the fluid homeostasis. This concept of transport of water across the cell membranes was suspected to be facilitated by channels or pores, which eventually led to the discovery of the water channels while working on membrane proteins of red blood cells in 1992 by Peter Agre and his colleagues. These water channels formerly named as CHIP28 are now called as aquaporin 1 (Brown, 2017). The discovery of aquaporins (AQPs) explained its primary role in water transport across biological membrane in response to the osmotic gradients formed as a result of active transport of the solute. This transport function exerted by aquaporins would be required for cell homeostasis to play a vital role in maintaining endothelial function (Uttara *et al*., 2009). There are thirteen distinct AQPs in mammals that are sub-divided into (Ishibashi, 2009).

Orthodox aquaporins

Conducts water only (AQP0, AQP1, AQP2, AQP4, AQP5, AQP6 and AQP8).

Aquaglyceroporins

Transport water and small neutral solutes, particularly glycerol (AQP3, AQP7, AQP9 and AQP10).

Unorthodox aquaporins

Indicated as unorthodox aquaporins due to their distinct evolutionary pathway and primary sequence distinctions (AQP11 or AQP12).

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The above isoforms of AQPs are expressed in cell types which are involved in transport of fluids like-epithelia and endothelia in kidney, lung, exocrine glands, eye (cornea, lens, ciliary epithelium), CNS (Astrocytes) and gastro-intestinal organs. They are also expressed in erythrocytes, certain leukocytes, adipocytes and skeletal muscle.

Stress arises as a reflexive response to unfavourable conditions in a particular environment in which the animal lives. Animals are exposed to various stressors that disrupt the homeostasis with oxidative stress being one among them. In addition to the excessive creation of reactive oxygen species (ROS) that antioxidants are unable to control, oxidative stress is also characterised as a disruption of the redox balance of cells (Pisoschi and Pop, 2015). Over the years, it has been widely established that the ROS produced in the biological system enters the cells by

diffusing freely through the lipid bilayer of the cell membrane and not through specific transporters or channels. This concept has changed considerably over time by the discovery of AQPs.

Cells implicated in inflammation, can suffer osmotic microenvironmental changes, resulting in increased cell hydraulic permeability and size, as well as variations in cytoskeletal structure (Maidhof *et al*., 2014). The participation of AQPs in multiple inflammatory processes, as evidenced by dysregulation in animal illnesses, reveals their novel significance in protection and response to various noxious stimuli, including bacterial infection. This discovery may provide a new key to resolving the understanding of host-pathogen interactions, as well as new situations for investigating the regulation of individual AQPs as targets for future pharmaceutical therapeutics (Meli *et al*., 2018). This review focuses on summarizing the evidences regarding the control that AQPs have over oxidative stress in physiological and pathological conditions in animals. The knowledge gaps have been identified to stimulate further research.

Importance of assessing stress in animals

Stress is a multi-dimensional phenomenon that challenges the homeostasis of the animal by affecting the body systems comprehensively. Exposure of animals to any acute or chronic stressors invariably leads to unfavourable consequences ranging from discomfort to death (Alberto *et al*., 2022). Ninan *et al*. (2019) in their studies on haematology in Gir cattle concluded that alterations due to metabolic, nutrient deficiency, physiological and health status can be compared for diagnostic and therapeutic purpose in different age and physiological states of Gir cattle breed, which are unique cattle breed adapted to existing climatic conditions. Stress evaluation has been crucial in production systems, research and in knowing the well-being of the animals and is needed in animals for developing therapeutic, nutritive and management strategies for better animal welfare.

Oxidative stress, significantly affects a wide range of living organisms. It develops when ROS production surpasses a live organism's antioxidant capability, which can result in numerous diseases (Alberto *et al*., 2022). Environmental agitations like nutritional deficiency, salinity, solar heat, radiation, drought, exposure to pesticides, heavy metals and herbicides stimulate the production of ROS, leading to oxidative distress that subsequently leads to various disease conditions (Desikan *et al*., 2005).

A growing body of literature clearly indicates that overproduction of ROS and the resulting oxidative stress is a major detrimental consequence of most common commercial stressors (Surai *et al*., 2019). Transportation of animals drives the affected animals to oxidative stress, thereby provoking morbidity, mortality, carcass trim loss and undesirable meat characteristics (Rosas-Valencia *et al*., 2019).

In dogs, sustained stress results in oxidative damage causing chronic disease conditions like; cardiovascular diseases, gastrointestinal diseases, immune dysfunction and development of abnormal behaviours (Fan *et al*., 2023). Animals subjected to chronic environmental stress exhibit alterations in endocrine function, basal metabolism, water and electrolyte metabolism, acid-base balance (Padodara and Ninan, 2013). In this regard, AQPs have a regulatory role in fluid homeostasis. Thus, the significance of assessing stress in animals plays an important role in identifying its impact on production as well as the welfare of the animal.

Different techniques used in quantifying Aquaporins

Quantification methods used to determine the aquaporins are Immunohistochemical analysis, Transmission electron microscopy visualization, Mass spectrometry, Gel electrophoresis, Immunoblot quantification, Liquid chromatography, Knockout animal models, Quantitative phenotypic assay, Inductively Coupled Plasma - Mass Spectrometry, Radio immuno assay, Western blotting and Sandwich ELISA.

Functions of Aquaporins in animals

The fundamental role of most aquaporins is to transport water molecules across the biological membranes in response to osmotic changes. A subset of aquaporins termed as aquaglyceroporins transports glycerol and evidence suggests that some aquaporins allow gases (CO_2, NH_3, NO, O_2) to pass (Verkman, 2013). These features have attracted researchers due to their physiological significance of transporting gases of biological relevance. In addition, many small solutes such as H_2O_2, arsenite and ions (K^+, Cl^-) are also being transported by some aquaporins. The AQPs that are able to conduct H_2O_2 and / or ammonia are called as peroxiporins and ammoniaporins / aqua ammoniaporins respectively (Tamma *et al*, 2018). Non-transporting functions for certain AQPs have been studied, such as cell to cell interactions, polarization of the cell membranes and regulation of the interacting proteins, such as the ion channels (Verkman, 2013).

Aquaporins (AQPs) feature ubiquitously in different species, organs, tissues and cells in the biological system.

i) AQPs are expressed particularly in cell types that involve in transport of fluid, such as epithelial cells in various organs and in some cell types that do not have vital role in fluid transport, such as adipocytes (Verkman *et al*, 2014).
ii) AQPs are associated with the functioning of gametes. In sperm, they are involved in osmo-adaptation, after the sperm enters reproductive tract of the female, which is decisive for activation of sperm motility, capacitation and for the fertilizing ability. AQPs play principal role in the maturation of oocytes (Delgado-Bermudez *et al*., 2022).
iii) In gastro-intestinal tissues, AQP1 in the epithelium of intra-hepatic bile duct is involved in bile formation, in lacteals of intestine involved in fat absorption and in

salivary gland microvascular endothelium taking part in secretion of saliva; AQP4 in parietal cells of stomach involved in acid/fluid secretion; AQP3 and AQP4 in colon surface epithelium involved in faecal dehydration; AQP5 in acinar cells in salivary glands take part in saliva secretion; and AQP8 in jejunal villi. AQP8 and AQP9 transcripts were localised in hepatocytes, indicating their role in regulation of hepatocyte volume and bile secretion (Ma and Verkman, 1999). AQPs regulation is carried out by the osmotic forces and AQPs have a major transcellular pathway for the bidirectional transport of water molecules by the digestive tract epithelium (Zhu *et al*., 2016).

iv) AQPs have a significant function in maintaining the fluid homeostasis in lungs (Wittekindt and Dietl, 2019). The expression levels of AQP1, AQP4 and AQP5 decreased in the respiratory tract in conditions like oxidative stress associated with heat-stress in buffaloes (Rebez *et al*., 2023).

v) AQP4 is relatively the most plenteous water channel in the central nervous system and is expressed in astrocytes and is involved in water movement, cell migration and neuro-excitation. AQP1 is localised in choroid plexus facilitating cerebrospinal fluid secretion and in neurons of dorsal root ganglion tuning pain perception (Papadopoulos and Verkman, 2013).

vi) In cardiovascular function. AQP1, AQP4, AQP7 and AQP9 express in the endothelial cells, vascular smooth muscle cells and heart. AQPs are expressed differentially in various cardiovascular tissues and take part in transmembrane transport of water, metabolism, cell migration and inflammatory response (Shangzu *et al*., 2022).

vii) The transport of solutes and water molecules through gut epithelia is regulated by different isoforms of AQPs and are characterised by their particular gastrointestinal tract distribution pattern (Zhu *et al*., 2016)

viii) AQP1 expression was found in renal epithelium particularly in the proximal tubule, descending limb of the loop of Henle and in descending vasa recta endothelium. Several evidences demonstrate that AQP2 is under the control of arginine vasopressin playing a critical role in reabsorption of water in kidney (Su *et al*., 2020). It has been found that the mice with deficient functional AQP2, AQP3, or AQP4 exhibit nephrogenic diabetes insipidus of various degrees due to reduced water permeability in the collecting duct. Mice that lack AQP7 and AQP8 have the ability to concentrate urine, although AQP7 null mice exhibit a unique defect in glycerol reabsorption (Verkman, 2006). Thus, AQPs are important in varied aspects of the concentrating mechanism of urine.

ix) In goats Shukla *et al*., (2023) identified AQP3 was higher in renal medulla as compared to renal cortex during summer season and opined AQP3 plays huge role in movement of water in kidney, particularly in renal medulla where anti-diuretic hormone acts in water reabsorption. Further the study suggested a seasonal variation in the expression of AQPs in goat's renal system.

Thus, numerous isoforms of AQPs have been identified and are differentially expressed and are involved in multiple physiological processes in animals, facilitating tissue-specific osmoregulation.

Regulatory role of Aquaporins in stressed animals

Aquaporins are membrane channels that are extensively distributed in various body systems. The 13 different AQPs, encoded by the genes AQP0–AQP12, identified in mammals help in regulation of important physiological functions in heart, kidney, brain, lung, digestive system and various other systems and have a functional role in stress associated with various pathological conditions. The underlying mechanisms of aquaporin involvement in various organ systems are discussed.

Cardiovascular system

Aquaporins in mammals expressed in heart have specific distribution pattern of each subtype in cardiomyocytes. Any dysfunction leads to wide range of disorders. In cardiac tissues of various animal species (mouse, rat, sheep, goat), AQP subtypes have been discovered and the first AQP (AQP1) was identified in a rat's cardiac tissue by Agre and co-workers (Verkerk *et al*., 2019). Recently, it has been found that aquaporins (AQP1, AQP4, AQP7 and AQP9) are localised in the endothelial cells, smooth muscle cells of vascular system and heart. The cardiac AQP localisation and expression depends on different factors that include; species, sex, development and aging (Verkerk *et al*., 2019). AQP are also involved in the pathology of related disease conditions like; cerebral ischemia, congestive heart failure and angiogenesis (Tie *et al*., 2017).

AQP1

In sheep and rabbits AQP1 is concentrated in microvascular endothelial cells and cardiomyocytes (Jonker *et al*., 2003, Ding *et al*., 2013). Myocardial ischemia and the severity of myocardial edema are consistent with AQP1 expression (Song *et al*., 2018). The dysfunction of mitochondria is considered to be the prominent feature of myocardial ischemia as this organelle is the prime contributor and major target for ROS inflicted damage (Kurian *et al*., 2016) leading to oxidative stress.

AQP4

Aquaporin4 maintains the water balance of cardiomyocytes. However, the role of AQP4 in cardiovascular disease is not studied and is poorly understood. AQP4 is distributed in intercalated discs, endothelial cells, sarcolemma and serosa of heart. AQP4 expression was down-regulated following myocardial injury, thus having a protective effect (Rutkovskiy *et al*., 2012). Butler *et al*. (2006) reported that AQP4 protein play significant role in myocardial oedema. It has been established that, when myocardial infarction with increased water content in cardiomyocytes induced myocardial oedema, AQP4 expression upregulated in cardiomyocytes (Song *et al*., 2018). Thus, the decrease in level of AQP4 in endoplasmic reticulum stress causes cardiac injury.

AQP7

For energy production, cardiomyocytes require fatty acids and glucose. AQPs of the sub-family, aquaglyceroporin allow the passage of glycerol playing significant role in energy regulation (Gladka *et al*., 2009). The most predominant aquaglyceroporin in heart is AQP7 which is upregulated in many conditions when energy and/or substrate are altered (Verkerk *et al*., 2019). AQP7 expression is upregulated in exercising rats (Verkerk *et al*., 2019). In cardiomyocytes, AQP7 may act as a facilitator of glycerol and alterations in AQP7 may elevate its susceptibility to hypertrophy and mortality rate. AQP7 can act as an original pathway for delivery of nutrients into heart and mediate toxicity of different poisons (Rutkovskiy *et al*., 2013).

AQP9

AQP9 is predominantly present in liver and not in heart, suggesting that AQP9 affects cardiac activity by decreased arsenic clearance by liver (Carbrey *et al*., 2009). AQP9 is localised in valvular tissue of subjects with infective endocarditis and their expression is related to the development of acute heart failure (Verkerk *et al*., 2019). Oxidative stress occurrence in the heart proves there is enhanced myocardial generation of H_2O_2 induced by active infective endocarditis (Ostrowski *et al*., 2013). In this context, it is found that expression of AQP9 can be a reliable prognostic marker in infective endocarditis. In polymicrobial sepsis, AQP9 may be used as a pharmacological target (Mohammad *et al*., 2022).

Digestive system

Fluid transfer such as secretion and absorption play crucial function in digestive system ensuring normal gut activities. Water transfer across the digestive epithelium is suggested to occur through AQPs and also through other channel mechanisms (Matsuzaki *et al*., 2004). Aquaporins play a vital role in maintaining intestinal stability by controlling the uptake and release of water molecules and small solutes. These aquaporins not only regulate cellular growth and movement but also contribute to processes like intestinal inflammation and tumour formation, underscoring their significant role in promoting intestinal well-being (Lv *et al*., 2022). Until now, at least 11 AQPs (AQP 1 to 11) are found to be expressed in stomach, small intestine and large intestine of the digestive system. Oxidative stress has a role in the pathogenesis of number of gastrointestinal disorders, like peptic ulcers, gastrointestinal malignancies and inflammatory bowel disease (Bhattacharyya *et al*., 2014).

AQP1

AQP1 is widely distributed in the endothelial cells of GI tract and plays crucial role in the transport of water between the GI tract mucosa and blood in addition to being involved in salivary secretion. AQP1 is found to be localised in the endothelial cells of the small intestine's central lacteals, which facilitates in formation of chylomicron, impairing adipose absorption. Several areas of the enteric nervous system, including the rat ileum and the ovine duodenum, have been reported to contain AQP1 (Volkart *et al*., 2023). AQP1 deletion is linked to a noticeably different bacterial stool microbiome composition and may affect mice's capacity to concentrate their stools (Volkart *et al*., 2023).

AQP1 was found in the small intestine and colon of buffalo and co-localization with enteric neurons in the jejunum, the ileum, the cecum and the colon were shown, suggesting involvement in osmoregulation in gastrointestinal physiology and also maturation of intestinal structures within the first week following birth (De Luca *et al*., 2015).

AQP3 and AQP4

The basolateral membrane of epithelial cells in the stomach and intestines is where AQP3 and AQP4 are primarily found. In the *Citrobacterium* rodent infection model, the results suggested that, AQP3-dependent H_2O_2 transport help in a ROS host defence mechanism (Thiagarajah *et al*., 2017). The preservation of intestinal epithelial barrier function depends heavily on AQP3. It modulates the import of extracellular H_2O_2, activating cyto-protective pathways such as epidermal growth factor receptor (EGFR). In intestinal damage, mice lacking AQP3 show aberrant H_2O_2 signalling, defective lamellipodia and focal adhesion formation, reduced wound healing and increased inflammation (Yde *et al*., 2021). AQP3 influences the formation of actin-driven lamellipodial projections in the injured cell model by influencing the membrane's permeability to hydrogen peroxide, aiding in endothelial cell migration and epithelial healing (Lv *et al*., 2022). Changing the location of AQPs may change the water homoeostasis of intestinal cells, which results in diarrhoea (Lv *et al*., 2022). AQPs are implicated in the pathophysiology of bile acid-induced diarrhoea (Yde *et al*., 2016).

AQP7, AQP8, AQP10 and AQP11

In small intestine and large intestine, AQP7, AQP8, AQP10 and AQP11 are dispersed in the enterocytes (Zhu *et al*., 2016). It has been found that, in intestinal tract, AQPs also participate in cell proliferation, related cell functions and participation in intestinal mucosal damage; regulation of cell signalling and innate mucosal immune responses (Lv *et al*., 2022).

AQP8 are involved in absorption of water in the intestine, the secretion of bile in liver and pancreatic juice in pancreas (Calamita *et al*., 2005). AQP8 is engaged in the metabolism of H_2O_2 and downregulating AQP8 may be a defence mechanism against extremely high levels of oxidative stress (Te *et al*., 2008). These facts suggest that H_2O_2 is a common mediator of the inflammatory process in the colon. Additionally, it was discovered that the colon of rats with IBD had downregulated levels of AQP1, AQP3 and AQP8 (Chao and Zhang, 2018).

The GI tract's aquaporin function should be further studied to develop innovative treatments and biomarkers to control fluid transport and to aid in the detection of GI illnesses.

Urinary system

It is well known that the pathogenesis of renal disorders may be influenced by the dysregulation of redox homeostasis and the excessive generation of free radicals. Oxidative stress is found to develop in animals with renal dysfunctions and is caused by an overall rise in ROS accompanied by a decline in antioxidant capacity (Tamma and Valenti, 2016). Ureteral obstruction induces renal injury and leads to oxidative stress (Kaeidi *et al*., 2020). Accordingly, many studies in animal models have explored the effect of unilateral ureteral obstruction-induced renal oxidative stress, inflammation and apoptosis. Unilateral Urethral Obstruction is linked to the severe downregulation of AQP2, AQP3, AQP4 and AQP1, which play significant roles in the impaired urinary concentrating capacity in the obstructed kidney. The downregulation of AQPs contribute to the impaired water reabsorption and urinary concentrating capacity in obstructive kidney disease, a serious and frequent clinical complication associated with the impaired renal tubular function in modulating fluid and electrolyte homeostasis. In oxidative stress associated with heat stressed chickens AQP2 levels increased in renal tissues (Rebez *et al*., 2023).

AQP1

Specifically caused by mitochondrial reactive oxygen species (mtROS), high glucose-induced cellular hypoxia was inhibited in the glomeruli of diabetic mice by mitochondrial blockades or manganese superoxide dismutase (MnSOD) overexpression, which boost the expression of AQP1. Endothelial cell overexpression of AQP1 inhibited the effects of hyperglycemia on cellular hypoxia and death (Sada *et al*., 2016).

AQP2

The extracellular cation, sodium and intracellular cation, potassium have significant physiological functions and any imbalance could lead to stress (Ninan *et al*., 2018). A study using rats found that water restriction lowered AQP2 while increasing plasma sodium and diuresis. This study offers novel evidence of the regulation of AQP-2 expression by renal endogenous Angiotensin II-oxidative stress in hypernatremic rats exposed to acute sodium overload (Della Penna *et al*., 2014). Bioinformatic data integration tools were used to identify the mechanisms causing AQP2 depletion and the research identified autophagy/apoptosis, oxidative stress and inflammatory signalling as crucial components of the system (Mak *et al*., 2023).

AQP11

Functional role of AQP11 includes the regulation of intracellular H_2O_2 homeostasis to avoid endoplasmic reticulum stress as a result of the functional identification of AQP11 as a peroxiporin. In the kidney's proximal tubular epithelial cells, AQP11 is abundantly expressed and associates with the endoplasmic reticulum. A more recent study reveals expression of loss-of-function mutant of water-specific AQP11, due to sudden juvenile death syndrome in mice model. It has been demonstrated that in AQP11 mutant mice the renal level of superoxide was elevated and that an antioxidant ameliorated ROS-related kidney injury. These findings suggest that the mechanism of progression of kidney injury involving an alteration of oxygen homeostasis leads to apoptosis (Hoshino *et al*., 2019).

Respiratory system

AQPs are channel proteins that facilitate transport of fluid in alveolar space, humidification of the air passage, fluid absorption in pleura and secretion of sub-mucosal glands (Song *et al*., 2017). The four AQPs, AQP1, AQP2, AQP4 and AQP5, expressed in the lungs under diverse physiological and pathological circumstances are associated with various lung disorders. In the peripheral lung and airways, water is transported via epithelia and endothelia during airway hydration, alveolar fluid transfer and submucosal gland secretion. The expression of AQP1 in microvascular endothelia, AQP3 and AQP4 in the airway epithelia and AQP5 in type I alveolar epithelial cells, submucosal gland acini and a minority of airway epithelial cells (Verkman, 2007).

AQP1

It has been established that AQP-1a is involved in transendothelial/transepithelial permeability of water and is the major pathway involved in water flux across pulmonary microvascular endothelium (Wittekindt and Dietl, 2019). Because it reduces pulmonary oedema and inflammation, AQP1 may protect against Ischemia-Reperfusion Injury (IRI)-induced lung injury. There may be a use for AQP1 upregulation in the treatment of ischemia-reperfusion injury to the lung (Wang *et al*., 2023a).

AQP5

In normal conditions, AQP-5 is localized in the respiratory epithelium mediating transcellular water permeability (Ma *et al*., 2015). Reactive oxygen or nitrogen species (ROS or RNS) and oxidative stress in the respiratory system increase the production of mediators of pulmonary inflammation and initiate or promote mechanisms of carcinogenesis (Valavanidis *et al*., 2013). It is possible to use AQP5 as a prognostic biomarker by understanding its involvement in the development of lung adenocarcinoma (Jaskiewicz *et al*., 2023). However, there is still paucity of information about the role of animal AQPs in respiratory system.

The regulatory AQPs in various body systems of stressed animals are presented in Table 1.

Regulatory role of Aquaporins in animal's resistance to drought conditions

Extreme weather condition like drought as a result of rising temperatures, are likely to decrease water quality for animal

Table 1: Regulatory AQPs in different body systems of stressed animals.

Organ system	Regulatory AQP in stressful conditions	Animal species	Reference
Cardiovascular system	AQP1	Ovine rabbit murine	Jonker *et al*., 2003; Ding *et al*., 2013; Song *et al*., 2018
	AQP4	Murine	Cheng *et al*., 2017; Rutkovskiy *et al*., 2012; Butler *et al*., 2006; Song *et al*., 2018
	AQP7	Murine	Verkerk *et al*., 2019; Hibuse *et al*., 2009; Rutkovskiy *et al*., 2013
	AQP9	Murine	Verkerk *et al*., 2019; Mohammad *et al*., 2022
Digestive system	AQP1	Murine swine	Liao *et al*., 2020; Volkart *et al*., 2023; Jin *et al*., 2006
	AQP3, AQP4	Murine	Thiagarajah *et al*., 2017; Yde *et al*., 2016; Yde *et al*., 2021; Lv *et al*., 2022 Guttman *et al*., 2007
	AQP7, AQP8, AQP10, AQP11	Murine	Te Velde *et al*., 2008; Chao and Zhang, 2018; Ricanek *et al*., 2015; Lv *et al*., 2022
Urinary system	AQP1	Murine	Sada *et al*., 2016
	AQP2	Murine	Della Penna *et al*., 2014; Mak *et al*., 2023
	AQP11	Murine	Atochina-Vasserman *et al*., 2013 Almasalmeh *et al*., 2014; Hoshino *et al*., 2019
Respiratory system	AQP1	Murine	Wang *et al*., 2023b

consumption, through increased concentration of pathogens, sediments, salts, nutrients or pollutants in water (Godde *et al*., 2021) impacting health and productivity of animals. Animals have developed varied adaptations to drought circumstances. These adaptations aid in their survival and growth in arid settings. Water homeostasis is one such mechanism that is regulated by aquaporins, even if their function in animal drought tolerance is less well understood than that of plants. Aquaporins help maintain cellular hydration and prevent dehydration in harsh environmental circumstances in animals by controlling water transport.

In summary, animals require aquaporins for water balance and stress tolerance during unfavourable environmental conditions. The attention of researchers is drawn favourably in understanding the complex regulatory role of aquaporins in animals affected by drought conditions, particularly in relation to defence mechanisms and drought adaption strategies.

CONCLUSION

The present review highlights the importance of AQPs and oxidative stress induced alterations of AQP isoforms in various body systems. Modulation of AQP functions at the target organ proves to be useful in treating and also in prevention of cardiovascular, digestive, renal and respiratory disease conditions associated with oxidative stress. This review of evidences related to the regulatory function of AQPs prove that there is still a necessity for more research efforts, as the key role of the various isoforms of AQPs in various organs needs to be better understood primarily in animals.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

Permission of IAEC not needed as this is a Review article.

Conflict of interest

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