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Functional Roles of Plant Protein Kinases in Signal Transduction Pathways during Abiotic and Biotic Stress

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Abstract

A process whereby a cell communicates and responses to external stimuli to alter plant growth, development, physiology and morphology is known as signal transduction. The integration of various signaling information and activities is important to generate a final response to the external stimuli. Protein kinases of protein phosphorylation are implicated in different signal transduction pathways in response to abiotic and biotic stress. Plants are always subjected to various ranges of abiotic and biotic stress. Protein phosphorylation is a post-translational modification process in which an amino acid residue of a protein is covalently modified by addition of a phosphate group involving an enzyme known as protein kinase. Protein kinases are among the most common cellular regulatory components of signal transduction in plants. Many studies demonstrate the prominent roles of protein kinases in the regulation of cell differentiation, growth and development of plant system. Plant growth is greatly affected by abiotic factors including low temperature, high salinity, osmotic stress, drought and biotic factors such as wounding as a result of invasion of various pathogens that eventually triggers the activation of plant defense system. Thus, this paper summarizes plant regulatory mechanisms of protein kinases via signal transduction process during abiotic and biotic stress. This paper also assesses the functional roles of protein kinases of phosphorylation in plant signaling pathways in response to abiotic and biotic stress. In a nutshell, in-depth knowledge about the roles of protein kinases is a prerequisite for the plant growth and development with their ability against various hostile environments.

Keywords: Protein kinases, Phosphorylation, Signal transduction, Abiotic and Biotic stress

Plant Protein Kinases in Various Signal Transduction Processes

Higher plants are always subjected to the abiotic and biotic stress to adapt the changeable environmental conditions by modulating many vital cellular functions and processes. Abiotic and biotic stress affect plant growth, yield and development. Abiotic stress is defined as the negative impact of the non-living factors on the living organisms in a specific environment. On the other hand, abiotic stress including light, gravity force, wind, temperature, drought, soil osmosticity and ionic ratios are among the challenges that plants must cope to survive. Biotic stress including predators, pathogens, pest herbivores, fungi and harmful insects are among living disturbances that influence the plant cellular processes in performing complex transduction processes against damage and diseases. Almost all plants have the biochemical factors necessary for stress tolerance acquisition to perceive stress and to generate signals that further transmitted into a series of responses via recognition of intercellular and intracellular signaling molecules. In response to the abiotic and biotic stress, the mechanisms on how the intracellular signaling molecules exhibit their responses on cells are known as signal transduction. During the signal transduction, a cascade of complex elements which is involved in several interacting components is required for initial signal recognition. A network of subsequent transduction of these signals stimulates the release of second messengers in the cell directly and indirectly. The production of second messenger affects the biochemical status of the signaling process by affecting the enzyme activity. By affecting protein kinase or

protein phosphatase activity, it leads to the physiological response in the cell [1]. Plant cells connect the adjacent cells through plasmodesmata which allow the signaling molecules to cross directly from cell to cell. Different signaling pathways which are generated from various stimuli in response to abiotic and biotic stress may share common signaling molecules and second messengers to achieve their objectives on their targets. This interdependence of signaling molecules from various types of signaling pathways promotes the crosstalk among cells, allowing a very complex modulation of responses to occur in plants. For example, calcium signaling pathway that couples with cyclic adenosine 3, 5-monophosphate [AMP] signaling pathway allows the generation of response in plants to occur. Plants exhibit different types of protein kinases to response to external stimuli. As a result, they give rise to the generation of various signals that are recognized and translated in the cells through complex networks of interaction. It is essential for plants to adapt to the changing environmental conditions. SNF1, CTR1, CK2, MAPK, NPK15, CDK are among the protein kinases that found in plants. Despite that, there are still some protein kinases that absent from plants, for example, cyclic nucleotide-dependent protein kinases and conventional protein tyrosine kinases. There are some unique plants protein kinases which are distinct from eukaryotes including receptor-like kinases [RLKs], calcium-dependent protein kinases or known as calmodulin-like domain protein kinases [CDPKs], TsI and PVPK1. With the presence of these protein kinases, they may possess some unique characteristics which are involved in plant growth and development. In fact, different observations occur in plants during the signal transduction pathways comparatively to eukaryotes. As a result, it exhibits divergence of developmental and environmental signals to which plants must respond. An obvious observation is detected in the

mechanism of signal transmission and transduction across plasma membrane in eukaryotes compared to plants. During the cell-surface signal transmission and transduction in plasma membrane involving the activation of receptor of Tyr kinase [RTKs], the ligand binding results in the autophosphorylation on the specific Tyr residue in eukaryotes [2]. Conversely, plants utilise RLKs to perform the same function as RTKs.

Changes of protein kinase activity in protein phosphorylation have been correlated with extracellular signals. Self-incompability [3], initiation of mitosis [4,5], isoprenoid biosynthesis [6], cytoplasmic streaming [7,8], sucrose phosphate synthase activity [9], MSERK1 activity [5] and phosphoenolpyruvate carboxylase activity [10] are the examples of regulation of cellular responses that involved protein kinases. ZmPK1 kinase with the identical extracellular domain of S-locus glycoproteins [SLG] in *Brassica* species is involved in the self-incompability expression in pistils [11]. Besides that, there are many signaling molecules which are common in many different pathways, such as Ca^{2+}, inositol phospholipids and G-proteins. Sometimes, some signaling protein complexes are permanent otherwise are formed immediately as a result of signaling. The signal transduction circuitry must present to enable functional biochemical activities and stability of morphogenesis to take place at places such as leaves, roots and flowers. Protein kinases are mainly constituted of larger group of phosphoryltransferases that transfer the terminal phosphate from ATP to the substrate protein. Protein phosphorylation induces the conformational changes in the protein kinase structure to regulate its activity [12].

In addition, plants protein kinases in protein phosphorylation are commonly affected by growth regulators. Indeed, protein kinases are involved in the regulation of cellular function. Protein kinase C [PKC] in plants has been found to be activated by phorbol ester, phorbol myristate acetate [PMA] and Ca^{2+}. During the addition of Ca^{2+} in the presence of phosphatidyl serine and PMA, PKC lowers the Km value and thus phosphorylates Histone H1 at serine residues [13]. On the other hand, protein kinase activity with Ca^{2+}-dependent characteristic, for example, Ca^{2+}-stimulated protein kinase activity is found in the membranes of pea shoot [14-16] as well as zucchini hypocotyls [17]. CDPKs in wheat germ [18] and corn have shown to be Ca^{2+}-sensitive [19]. These protein kinases are depended on the concentration of cytoplasmic Ca2+ for the development and metabolic changes in plant cells [20]. Likewise, the interest in the study of Ca^{2+}-activated phosphorylation in soybean [21] has also led to the discovery of CDPKs which are unique [22,23]. In short, different concentrations of Ca^{2+} in the cytoplasma promote and inhibit protein kinases activity in plants. The changes of cytosolic Ca^{2+} level in response to various environmental stimuli such as phytochrome treatment, temperature and water stress, pathogenic infection, light, osmotic pressure, soil quality and pH alter the protein phosphorylation in plant cells. CDPKs with N-terminal kinase catalytic domain contiguous with a terminal calmodulin-like Ca^{2+}-binding domain is a good example of calcium-dependent phosphorylation [24]. CDPKs require Ca^{2+} without the agency of calmodulin. On the other hand, another type of CDPK with the sequence of CB1 has been identified in plant system. It has been suggested that CB1 with the catalytic and calmodulin-binding domains may contain at least two different routes which are able to change the Ca^{2+} level as well as alter the protein phosphorylation [25]. The detail of the dual functional roles of CDPKs during abiotic and biotic stress is explained in the later part of this review paper.

Other homologous examples of equivalent function to the CDPKs in plants such as AtAK1, OsSpk and DcPK431 have been isolated from *Arabidopsis*, rice and carrot, respectively [26]. Plants may mediate early signaling events via highly conserved cytoplasmic kinase cascade in response to variety of stimuli. The supports for the identification of cytoplasmic kinase cascade in plants are mitogen-activated protein kinases [MAPKs] and Constitutive Triple Response 1 [Ctr1]. Wang and coworkers [27] reported that mitogen-activated protein kinase 3 [MPK3] and mitogen-activated protein kinase 6 [MPK6] together with their MKK4/MKK5-MPK3/MPK6 cascade in Arabidopsis possess important functional roles in the regulation of stomatal development, patterning and stress-responsive pathways. Loss function of MKK4/MKK5-MPK3/MPK6 cascade disrupts coordinated cell fate specification of stomata that results in the formation of clustered stomata. In contrast, the activation of MKK4/MKK5-MPK3/MPK6 cascade suppresses the asymmetrical cell division and stomatal cell fate specification which in return, results in the lack of stomatal differentiation. On the other hand, Ctr1, a Raf family of protein kinase is a negative regulator of ethylene response pathway in *Arabidopsis*. The establishment of a complete signaling pathway suggested that the cytoplasmic kinase cascade is needed for signal transduction of ethylene [28]. Despite the involvement of protein kinases, there are crosstalk between different hormone-dependent signaling pathways involving plant hormones such as ethylene, cytokinin, auxin, gibberellins, abscisic acid [ABA] and abiotic stress signal pathways including cold, salt, drought and pathogens attack. The combined interaction between classical hormones and protein kinases is responsible for new activities that have not been seen before when an individual hormone is exogenously applied. For example, the ethylene-insensitive mutant or known as pin2 displays defective auxin responses while the auxin-resistant mutant, axr1 exhibits resistance to exogenous ethylene.

Another type of protein kinase, MAPKs are the signaling modules that phosphorylate specific serine/threonine residues to regulate various cellular functions and activities. MAPKs are activated in response to abiotic stress such as drought, salt and osmotic stress. In the MAPKs pathway, the MAPK cascade constitutes of three functionally interlinked protein kinases, MAPK kinase kinase [MAPKKK], MAPK kinase [MAPKK] and MAPK. The activated MAPKKK phosphorylates and activates MAPKK which then in return phosphorylates and activates a MAPK, followed by activation of specific signaling molecules such as transcription factors to induce cellular responses from the nucleus of a cell. The example of MAPKs involved in drought stress signaling is the OsMSRMK2 transcripts that play a pivotal role during the drought tolerance in rice [29]. On the other hand, NPK1 gene which is MAPKKK ANP orthologue is expressed in active form in *Arabidopsis*. It is among the MAPK modules that used in the salt and osmotic stress signaling pathways in plant system [30]. Different signal transduction pathways response independently or form the crosstalk among themselves to solve the problems of different abiotic stress. The detail of the functional roles of MAPKs is explained further in the later part of this review paper.

Functional Roles of Protein Kinases of Phosphorylation in Plant Signaling Pathways in Response to Abiotic and Biotic Stress

Roles of plant protein kinases during abiotic and biotic stress are important. Drought and osmotic stress that complicate the plant photosynthetic process are able to decline and interfere with nutrient

availability which leads to physiological drought and ion intoxication. Many evidences exhibit the essential of protein phosphorylation at the early and later stage of the signaling pathways that lead to plant defense responses. No doubt that protein phosphorylation is involved in the abiotic stress which includes high salinity, high and low osmolarity, extreme temperature, drought, ozone exposure and ultraviolet irradiation but it is also implicated in the plant defense signaling pathways. Fowler and Thomashow [31,32] demonstrated that with low and freezing temperatures, they cause osmotic stress that would affect the plant metabolism. However, to prevent the osmotic stress, the stomata minimizes water uptake. To maintain osmotic homeostatis, plants regulate gene expression involving unique changes in transcript levels of some specific genes such as protein kinases that control abiotic stress tolerance mechanisms [33].

Protein kinases are implicated in abiotic stress such as cold, salt and drought as well as in biotic stress involving living disturbances that causes wounding as a result of the invasion of predators, pathogens, pest herbivores, fungi and harmful insects. During abiotic stress, signal transduction that contains the reversible protein phosphorylation is implicated in many signaling protein kinase cascades. Changes of protein phosphorylation are observed after plant cells expose to the abiotic and biotic stress. The protein phosphorylation that involved in the regulation of physiology, morphology and gene expression are commonly responded to diverse cellular processes, including cell proliferation, growth and development, cell death and stress response. In fact, some of the functions of protein kinases have been found to be crosstalk between the abiotic and biotic stress signal pathways.

Roles of Plant Protein Kinases in Response to Abiotic Stress

MAPKs are activated by numbers of abiotic stress. MAPK cascade plays an important role in response to various abiotic stress including cold, drought, salt and water stress. CTR1, ANP1-3 and AtMEKK are among the three major types of MAPKKK that have been identified to response to abiotic stress such as cold, drought and mechanical stimulation [34]. A number of protein kinases with conserved group of serine/threonine protein kinase domain, which possess homologous sequence to MAPKs have been isolated from different plant species that are implicated in many signal transduction processes. MAPKs are involved in many cellular processes including development, hormonal, biotic and abiotic stress signaling [35]. Additionally, quite a number of MAPKs that are belonged to animals and yeasts are implicated in the cell differentiation, cell division as well as stress responses. Some MAPKs with highly conserved threonine and tyrosine domains that located in the sub-domain VIII are able to perform tyrosine and threonine phosphorylations. This dual specific MAPKK is activated by serine/threonine MAPKKK [36,37]. These kinase cascades mediate distinct signal transduction and transmission pathways. Jonak et al. [38] suggested there is a specific type of MAPK pathway is involved in the signaling of cold and drought stress in alfalfa plants. P44MMK4 kinase is activated during cold and drought treatments. Notably, P44MMK4 kinase is rapidly activated by low temperature and dehydration. Interestingly, another gene, ATMPK3 which encodes an *Arabidopsis* MAPK is found to accumulate during transcription after exposed to cold, drought, salt and touch stress [34]. Although plant hormones such as ABA and protein kinases including MAPKs are responsible for the role during cold and drought conditions, they are, however, operated independently in different pathways. ABA is a hormone that implies as a negative regulator of seed germination and

also involves in abiotic stress such as drought. The main functions of ABA are consisted of controlling plant water balance and osmotic stress besides toleration of the cellular dehydration. ABA influences ion transportation to stomatal guard cells in order to regulate the opening and closing of stomatal as a result of changing water availability from the environment. Tallman [39], Kearns and Assmann [40] reported that closing of stomata is due to ABA when the guard cells lose osmoticum in the form of K^+ to become less turgid. Application of ABA to the guard cells stimulates the increment of cytosolic free Ca^{2+} to allow the closing of stomata. Likewise, Irving and coworker [41] proved that the stomatal movements are triggered by changes of cytosolic pH. ABA is a regulatory molecule involved in the modulation of osmotic stress tolerance using cellular dehydrogenated tolerance genes to control the water balance through the opening and closing of stomata. Similarly, Hugouvieux et al. [42] also identified the function of ABA in the stimulation of the stomatal closing by losing the turgor pressure in the leaf guard cells. Based on their study, they proved the abh1 mutants of *Arabidopsis* with enhanced ABA responsiveness lose water at much slower rate than the wild type parents. The osmotic stress causes the increment of ABA biosynthesis. Therefore, it is no doubt that ABA biosynthesis is required for drought and thermotolerance. Additionally, ABA is also enhanced by presence of salt but to a lesser extent by cold stress [43-45]. ABA is thus, important in mediating responses to cold and water stress besides MAPKs.

When Jonak and coworker [38] sprayed alfalfa with ABA during the cold and drought treatments, neither the induction of MMK4 gene nor the activation of P44MMK4 kinase was observed. It indicated that the cold and drought-induced activation of P44MMK4 kinase are produced independently of ABA in the protein kinase pathway. The experiment also implied the presence of ABA-dependent and ABA-independent pathways in response to low temperature and dehydration. In *Arabidopsis*, the MAPK cascade consists of AtMEKK1, AtMEK1/AtMKK2 and AtMPK4. Salt stress induces the expression and activity of AtMEKK1 which activates AtMPK4 in vitro. Ichimura et al. [46,47] reviewed that AtMPK4 is activated by low temperature, low humidity, osmotic stress and touch. Likewise, similar study also conducted by Mizoguchi and coworkers [34] where the *Arabidopsis* MAP kinase kinase 1 [MEKK1] is induced by cold, salt, drought and touch, respectively. Another protein kinase cascade, MEKK-MAPK kinase 2 [MKK2] which consisted of MPK4/MPK6 is responsible as part of cold and salt stress [47-49]. Tamura and coworker [50] reported a type of receptor-like protein kinase or known as NtC7 in tobacco is involved in the abiotic stress where this membrane-localized receptor-like protein is responsible for the stress responses during salt and osmotic tolerances. Beside the involvement of MAPKs in the signaling of touch, cold, salt, water stress, there are also other MAPKs exhibit dual functional roles during exposure of plant cells to biotic stress and fungal elicitor that will be discussed later in this review paper [34,51].

CDPKs and their upstream kinases have shown their activation under various stress [52]. CDPKs are implicated in plant defense to cope with cold, mechanical stimulation and oxidative stress [53-55]. For example, the studies of stress-responsive gene expression and characterization of CDPK suggested that some stress-induced Ca2+ signals are perceived and transmitted by CDPKs. In short, CDPKs are activated by abiotic stress [56]. The involvement of CDPKs in stress-induced gene transcription was demonstrated using a maize leaf protoplast transient expression system [57]. Indeed, there are many different CDPKs found in the genome of *Arabidopsis* where AtCDPK1

and AtCDPK2 are the genes implicated in salt and drought stress signaling pathways [57,58]. AtCDPK1 activates a barley ABA-responsive promoter fusion. The expression of CDPK induces the expression of a rice stress-responsive genes, RAB16 [59] and HVA1 in the maize protoplasts [57]. The up-regulation of RAB16 and HVA1 may mediate by CDPKs. In fact, the report indicated the responsible of CDPKs in the implication of stress tolerance in plant systems. A potential CDPK gene known as StCDPK5 has been reported by Kobayashi et al. [60] that able to phosphorylate the NADPH oxidase, StRBOHB during oxidative stress in potato, *Solanum tuberosum*. The increase in calcium level as the secondary signal molecule is perceived by various CDPKs. Calcium is a universal secondary messenger that influences the roles of CDPKs to response to abiotic and biotic stress. The fluctuation in cytosolic Ca2+ levels affects the CDPKs in which they modify the phosphorylation of substrate proteins that are implicated in the plant stress tolerances. CDPKs are one of the serine/threonine protein kinases which exhibit a C-terminal calmodulin-like domain with the presence up to 4EF hand motifs that bind Ca2+ directly. Some CDPKs with the N-terminal myristoylation motif have potential association with membranes. Additionally, there is a membrane associated CDPK activated by the cold treatment [61]. On the other hand, the overexpression of OSCDPK7 kinase gene in rice at the mRNA level is specifically induced by cold, drought and salt stress signaling [59].

Roles of Plant Protein Kinases in Response to Biotic Stress

Protein phosphorylation by protein kinases is known to implicate prominent role in many signal transduction pathways in plants especially in defense responses. Biotic has many stress ways to impose constraints on plant growth and development. Disease resistance in plants is always associated with the replication and movement of pathogens along the plant circulatory system which consists of phloem and xylem. The pathogenic responses generate specific gene mechanisms such as cross-linking of cell wall proteins, activation of protein kinases and increase expression of various plant protection and defense genes [62,63]. Zhang and Klessig [64,65] were able to provide evidences of the involvement of protein kinases in the activation of plant defense. Evidence of the potential roles of protein kinases such as CDPKs involved in the stress tolerance in plant defense system is the barley CDPK paralogs, HVCDPK3 and HVCDPK4. Their involvement in the plant defense response plays the antagonistic roles at the early phase of powdery mildew pathogenesis [66]. Similarly, the wheat CDPK genes such as TaCPK2 and TcCPK5 have the potential roles in the wheat powdery mildew resistance even though some CDPKs possess essential functional roles in response to abiotic stress such as cold, salt and frought stress. It is notably proven that some plants protein kinases are involved in the crosslink between abiotic and biotic stress.

Another protein kinase, the salicylic acid-induced protein kinase [SIPK], a member of MAP kinase family is activated in response to various pathogen-associated stimuli especially the pathogen elicitor from *Phytophthora sp*, bacterial harpin and tobacco mosaic virus [TMV] [64,65,67,68] Additionally, it is also expressed response toward wounding [64,65]. This protein kinase is therefore, activated in multiple signaling pathways according to Zhang and Klessig [64,65]. The activation of SIPK is generally regulated during posttranslational level via dual phosphorylation of threonine and tyrosine residues in the conserved motif of TEY found between sub-domain VII and VIII of the kinase catalytic domain.

Another protein kinase termed as wounding-induced protein kinase [WIPK] is being activated during wounding stress. The transcripts of WIPK are accumulated after wounding stress occurred [68]. WIPK has been hypothesized to enhance a wounding-activated kinase of approximately 46 kDa. In the same finding, WIPK activation is induced by pathogen elicitor such as cell wall-derived carbohydrate elicitor from *Phytophthora spp* as well as TMV. WIPK is therefore, being controlled at the multiple levels. After the TMV infection on plants, WIPK activity is drastically improved transcriptional and translational levels and finally increased the posttranslational phosphorylation [70,71,73]. Transgenic plant of tobacco with the depressed WIPK activity exhibits the increment of salicylic acid production and thus, provokes the induction of acidic PR1 and PR2 genes upon wounding. Comparatively, the wounding wild type tobacco did not show any induction of salicylic acid production suggested that protein phosphorylation mediated crosstalk between wound-and-pathogen-induced signaling pathways. Induction of acidic defense genes, PR1 and PR2 occurs after the pathogen elicitors invaded the plant physiological processes. Protein kinase in protein phosphorylation is playing prominent role in the development and induction of PR1 gene expression in tobacco plants. Thus, this protein kinase appears to be well-function in the defense signaling pathway [64,65,68].

Likewise, Usami et al. [69] and Seo et al. [70] studied the activation of MAPK activity occurred in tobacco and tomato leaves in response to biotic stress of wounding. Mounting evidences indicates that fungal elicitors trigger rapid and transient protein phosphorylation in parsley and tomato cell suspension cultures [71,72]. Martin et al. [73] and Song et al. [74] demonstrated the role of tomato Pto and rice Xa21 resistance genes which encoded serine/threonine protein kinases in the plant defense response signaling pathway via protein phosphorylation. Pto kinase requires an LRR-containing cytoplasmic protein encoded by Prf gene that responsible against Pseudomonas syrinage pv tomato by expressing corresponding avirulence gene, avrPto [75-78]. Prf may interact with Pto kinase to perceive and transmit the virulence signal, whereas a receptor-like kinase with an intracellular kinase domain and putative extracellular LRR encoded by rice Xa21 may contain the combined functions of Pto and Prf [74]. Ample protein kinases have been implicated in plant disease resistance, such as the PR5K receptor-like kinase of *Arabidopsis* and a receptor-like kinase [SFR2] of *Brassica oleracea* [79,80,81]. PR5K receptor-like kinase contains an extracellular domain homologous to an antimicrobial protein known as PR-5 protein that is possibly involved in the perception of pathogen signals. In addition, SFR2 receptor-like kinase may contribute to the signaling of plant defense after it rapidly induced by wounding and bacterial infection. Similarly, the activation of protein phosphorylation of G/HBF-1, a soybean bZIP transcription factor by a bacterial pathogen-induced serine/threonine kinase occurs in order to enhance its binding activity to the cha/cone synthase chs15 promoter that may regulate by MAPK cascade, which has been associated with plant defense signaling [34,38]. Suzuki and Shinshi [51] activated a 47 kDa putative MAPK kinase by tyrosine phosphorylation after fungal elicitor treatment on tobacco cells. However, the activation of this 47 kDa kinase was inhibited by staurosporine and a Ca2+channel blocker, gadolinium [Gd2+]. The upstream kinases and Ca2+ may implicate in the activation of 47 kDa kinase during plant defense stress against various pathogens.

Besides that, the *Arabidopsis* MAP kinase cascades that comprise of MEKK1-MKK4/MKK5-MPK3/MPK6 regulate pathogen defense response pathway through the gene expression of WRKY22 and WRKY9 according to Asai et al. [82] and Nuhse et al. [83]. In addition, MPK3 and MPK6 are also involved in abiotic stress. MPK3 is also functioned in ABA signaling pathway during the post-germination stage as reported by Lu et al. [84]. Moreover, MPK6 is activated by oxidative stress in *Arabidopsis* cultured cells [85]. In *Arabidopsis*, MPK3, MPK4 as well as MPK6 are activated by bacterial and fungal pathogen-associated molecular patterns and reactive oxygen species [ROS] [30,83,86]. ROS are species of oxygen which are in a more reactive state than molecular oxygen. ROS are implicated in the induction of programmed cell death or necrosis. They participate in many induction or suppression of expressed genes and activation of cell signaling responses involving protein kinases such as MAPKs. MAPKs are modulated by ROS. The ROS production is one of the earliest responses in plants during pathogen infection including wounding. ROS, in the form of hydrogen peroxide is a crucial signaling molecule in animal and plant kingdoms. ROS in plants, are particularly important in plant host defense system, orchestrate programmed cell death to control the spread of invading and infection of pathogens that cause the cellular damage if remain uncontrolled. In contrast to plant system, ROS also responsible as signaling molecules due to their small size and ability to diffuse across short distances. MPK3 and MPK6 activities in ROS signaling are influenced by *Arabidopsis* serine/threonine kinase, termed as OXI1, whose kinase activity is induced by H_2O_2. With the presence of OXI1 in *Arabidopsis*, they exhibit tolerance to infection by virulent fungal pathogens.

Another Arabidopsis MAPKKK, ANP1 is involved in the activation of MPK3 and MPK6 through H2O2. The stable overexpression of ANP1 exhibits the plant resistance to heat shock, freezing and salt stress [30]. Similarly, Nicotiana protein kinase 1 [NPK1] which overexpressed by tobacco homologous to ANP1 is able to improve tolerance of freezing, heat, drought and high salt conditions [30].

Plants resist different pathogens such as fungi, bacteria and viruses that are often depended on whether the plants are able to recognize the pathogens during the early stage of infection. Plants generate ROS by various processes in different cellular compartments to control various biological programs [87]. After the pathogens attack, ROS are rapidly produced followed by hypersensitive response [HR], a localized programmed cell death at the site of infection. Some ROS species are toxic by-products of aerobic metabolism. They are implicated in the ABA signaling and disease resistance responses [88,89]. ROS are also produced beneficially for plants defense. The plant cells increase the ROS levels through the activation of ROS-generating oxidase and suppression of ROS-scavenging enzymes. Higher ROS levels in the cells as a result of various pathogens attack may activate the MAPKs signaling pathway to induce the pathogenesis-related [PR] gene. When parsley cells are infected by fungal elicitor, Pep13, it triggers the ROS production, phytoalexins and MAPKs induction as well as PR gene expression. The activation of MAPK where the Pep13 is induced, stimulates the PR gene during resistance toward fungal and bacterial pathogens [88,89]. Conclusively, MAPKs are one of the protein kinases that play prominent dual functional roles in the signal transduction pathways of abiotic and biotic stress. Many abiotic and biotic stress such as osmotic stress, cold, high salt, drought and wounding are therefore, activated by various MAPKs in *Arabidopsis* [90]. MAPK cascade of MEKK1-MKK2-MPK4/MPK6 is reported to resist cold and salt stress [48]. Additionally, MEKK1 is transcriptionally induced by salt stress, drought, cold and wounding [34] to interact with MKK1, MKK2 and MKK4 [46]. MEKK1 mediates the activation of MPK3 and MPK6 through MKK4 and MKK5 [82] but activates MPK4 and MPK6 in MKK2-dependent manner during abiotic stress [48]. MEKK1 is activated by wounding, cold, drought and salt stress to phosphorylate MPK4 [48,91]. In conclusion, MAPKs appear to be conserved in higher eukaryotes and may mediate host defense responses across animals and plants during abiotic and biotic stress. Summary of the functional roles of some plant protein kinases are stated in Table 1.

Protein kinase	External stimuli	Role	Reference
ANP1	Heat shock, freezing and salt stress	Involves in the activation of MPK3 and MPK6 through H2O2	Kovtun et al. [30]
NPK1	Freezing, heat, drought and high salt conditions	Abiotic stress tolerances in tobacco	Kovtun et al. [30]
Arabidopsis MAP kinase encoded by ATMPK3	Cold, drought, salt and touch stress	Arabidopsis MAP kinase is found to accumulate during transcription	Mizoguchi et al.[34]
CTR1, ANP1-3, AtMEKK	Abiotic stress including cold, drought, salt, water stress and mechanical stimulation	Cell development, hormonal, biotic and abiotic stress signaling pathway	Mizoguchi et al.[34]; Ligterink and Hirt, [35]
P44MMK4 kinase	Low temperature and dehydration	Drought and cold treatments	Jonak et al.[38]
AtMEKK1	Salt stress, low temperature, low humidity, osmotic stress, touch and wounding	Stimulates the expression and activity of AtMPK4	Ichimura et al.[46] and [47]
MEKK-MAPK kinase 2 [MKK2]	Cold and salt stress	Abiotic stress tolerances	Ichimura et al.[47] and [49]; Teige et al.[48]
NtC7	Wound, salt and osmotic stress	Abiotic stress tolerances in tobacco	Tamura et al.[50]
CDPKs encoded by AtCDPK1 and AtCDPK2 genes	Salt and drought stress	Enhances the expression of a rice stress-responsive genes, RAB16 and HVA1 in the maize protoplasts	Sheen [57]; Urao et al.[58]; Saijo et al. [59]
OSCDPK7	Cold, drought and salt stress	Abiotic stress tolerances in rice	Saijo et al.[59]

HVCDPK3 and HVCDPK4	Pathogenic-associated stimuli	Antagonistic roles in early phase of powdery mildew pathogenesis	Freymark et al.[66]
SIPK	Wounding stress and pathogenic-associated stimuli: pathogen elicitor from Phytophthora sp, bacterial harpin and tobacco mosaic virus infection	Pathogen-associated responses	Zhang and Klessig, [64, 65, 67]; Zhang et al.[68]
Protein kinase encoded by acidic defense genes, PR1 and PR2	Plant defense and pathogenic-associated stimuli	PR1 gene expression in tobacco in the defense signaling pathway	Zhang and Klessig, [64, 65]; Zhang et al.[68]
WIPK	Wounding stress and pathogen elicitor such as cell wall-derived [CED] carbohydrate elicitor from Phytophthora spp and tobacco mosaic virus infection	Pathogen-associated responses	Zhang et al.[68]
MAPK	Wounding	Activation of MAPK activity occurred in tobacco and tomato leaves	Usami et al.[69]; Seo et al.[70]
Serine/threonine protein kinases encoded by tomato Pto and rice Xa21 resistance genes	Pathogenic-associated stimuli	Plant defense response signaling pathway	Martin et al.[73]; Song et al.[74]
PR5K receptor-like kinase of Arabidopsis and a receptor-like kinase [SFR2] of Brassica oleracea	Wounding and bacterial infection	Pathogen signaling pathways	Wang et al.[79]; Pastuglia et al.[80, 81]
MEKK1-MKK4/MKK5-MPK3/MPK6 cascades	Pathogenic-associated stimuli	Stimulate the expression of WRKY22 and WRKY29	Asai et al.[82]; Nuhse et al.[83]
MPK3, MPK4, MPK6	Bacterial and fungal pathogen-associated stimuli and reactive oxygen species [ROS]	Plant defense response signaling pathway	Kovtun et al.[30]; Nuhse et al.[83]; Desikan et al.[86]
MAPKs	Osmotic stress, cold, high salt, drought and wounding	Abiotic and biotic stress tolerances in Arabidopsis	Nakagami et al.[90]
MEKK1	Wounding, cold, drought and salt stress	MPK4 protein phosphorylation	Teige et al.[48]; Matsuoka et al.[91]

Table 1: Summary of the role of some plant protein kinases.

Conclusion

Signal transduction has become one of the interesting topics of research in plant biology in the recent years. Protein kinases are the commonly found transduction components interpreting signals in plant cells. Different plant protein kinases act on various types of substrates in protein phosphorylation to regulate and mediate signal transduction processes in many environmental variables during abiotic and biotic stress. Plants protein kinases cope and manage with their environmental stress such as high salinity, changes of temperatures, drought, light, soil pH and quality, growth inhibitors and promoters, carbon dioxide, oxygen, water status and pest diseases as well as wounding. Integration of various forms of signaling regulatory metabolite in plant cells including protein kinase through a complex signal network system crosstalk between the abiotic and biotic stress is pivotal to ensure many final stress responses are properly generated for signal recognition and transduction to produce healthier physiological growth and development in plant system.

References

1. Trewavas AJ, Malho R (1997) Signal Perception and Transduction: The Origin of the Phenotype. Plant Cell 9: 1181-1195.
2. van der Geer P, Hunter T, Lindberg RA (1994) Receptor protein-tyrosine kinases and their signal transduction pathways. Annu Rev Cell Biol 10: 251-337.
3. Goring DR, Glavin TL, Schafer U, Rothstein SJ (1993) An S receptor kinase gene in self-compatible Brassica napus has a 1-bp deletion. Plant Cell 5: 531-539.
4. Li H, Roux SJ (1992) Casein kinase II protein kinase is bound to lamina-matrix and phosphorylates lamin-like protein in isolated pea nuclei. Proc Natl Acad Sci U S A 89: 8434-8438.
5. Duerr B, Gawienowski M, Ropp T, Jacobs T (1993) MsERK1: a mitogen-activated protein kinase from a flowering plant. Plant Cell 5: 87-96.
6. MacKintosh RW, Davies SP, Clarke PR, Weekes J, Gillespie JG, et al. (1992) Evidence for a protein kinase cascade in higher plants: 3-Hydroxy-3-methylglutaryl-CoA reductase kinase. Eur J Biochem 209: 923-931.
7. Tominga Y, Wayne R, Tung HYL, Tazawa M (1987) Phosphorylation-dephosphorylation is involved in Ca2+-controlled cytoplasmic streaming in Characean cells. Protoplasma 136: 161-169.
8. McCurdy DW, Harmon AC (1992) Calcium-dependent protein kinase in the green alga Chara. Planta 188: 54-61.
9. Huber, SC, Huber JL (1991) Regulation of maize leaf sucrose-phosphate synthase by protein phosphorylation. Plant Cell Physiol 32: 319-326.
10. Bakrim N, Echevarria C, Cretin C, Arrio-Dupont M, Pierre JN et al. (1992) Regulatory phosphorylation of Sorghum leaf phosphoenolpyruvate carboxylase. Identification of the protein-serine kinase and some elements of the signal-transduction cascade. Eur J Biochem 204(2): 821-830.
11. Ebert PR, Anderson MA, Bernatzky R, Altschuler M, Clarke AE (1989) Genetic polymorphism of self-incompatibility in flowering plants. Cell 56: 255-262.

12. Sprang SR, Acharya KR, Goldsmith EJ, Stuart DI, Varvill K, et al. (1988) Structural changes in glycogen phosphorylase induced by phosphorylation. Nature 336: 215-221.

13. Chandok MR, Sopory SK (1998) ZmcPKC70, a protein kinase C-type enzyme from maize. Biochemical characterization, regulation by phorbol 12-myristate 13-acetate and its possible involvement in nitrate reductase gene expression. J Biol Chem 273: 19235-19242.

14. Hetherington A, Trewavas A (1982) Calcium-dependent protein kinase in pea shoot membranes. FEBS Lett 145: 67-71.

15. Hetherington AM, Trewavas A (1984) Activation of a pea membrane protein kinase by calcium ions. Planta 161: 409-417.

16. Hetherington A, Trewavas A (1984) The regulation of membrane-bound protein kinases by phospholipid and calcium. Annu Proc Phytochem Soc Eur 24: 181-197.

17. Salimath BP, Marmé D (1983) Protein phosphorylation and its regulation by calcium and calmodulin in membrane fractions from zucchini hypocotyls. Planta 158: 560-568.

18. Polya GM, Davies JR, Micucci V (1983) Properties of a calmodulin-activated Ca2+-dependent protein kinase from wheat germ. Biochim Biophys Acta 761: 1-12.

19. Veluthambi K, Poovaiah BW (1984) Calcium-promoted protein phosphorylation in plants. Science 223: 167-169.

20. Hepler PK, Wayne RO (1985) Calcium and plant development. Annu Rev Plant Physiol 36: 379-439.

21. Putnam-Evans CL, Harmon AC, Cormier MJ (1986) Calcium-dependent protein phosphorylation in suspension cultured soybean cells. In Molecular and Cellular Aspects of Calcium in Plant Development (ed. A. J. Trewavas) New York: Plenum Press 99-106.

22. Roberts DM1 (1993) Protein kinases with calmodulin-like domains: novel targets of calcium signals in plants. Curr Opin Cell Biol 5: 242-246.

23. Harper JF, Binder BM, Sussman MR (1993) Calcium and lipid regulation of an Arabidopsis protein kinase expressed in Escherichia coli. Biochemistry 32: 3282-3290.

24. Harper JF, Sussman MR, Schaller GE, Putnam-Evans C, Charbonneau H, et al. (1991) A calcium-dependent protein kinase with a regulatory domain similar to calmodulin. Science 252: 951-954.

25. Watillon B, Kettmann R, Boxus P, Burny A (1993) A calcium/calmodulin-binding serine/threonine protein kinase homologous to the mammalian type II calcium/calmodulin-dependent protein kinase is expressed in plant cells. Plant Physiol 101: 1381-1384.

26. Hanks SK, Hunter T (1995) Protein kinases 6. The eukaryotic protein kinase superfamily: kinase (catalytic) domain structure and classification. FASEB J 9: 576-596.

27. Wang H, Ngwenyama N, Liu Y, Walker JC, Zhang S (2007) Stomatal development and patterning are regulated by environmentally responsive mitogen-activated protein kinases in Arabidopsis. Plant Cell 19: 63-73.

28. Daum G, Eisenmann-Tappe I, Fries HW, Troppmair J, Rapp UR (1994) The ins and outs of Raf kinases. Trends Biochem Sci 19: 474-480.

29. Agrawal GK, Rakwal R, Iwahashi H (2002) Isolation of novel rice (Oryza sativa L.) multiple stress responsive MAP kinase gene, OsMSRMK, whose mRNA accumulates rapidly in response to environmental cues. Biochem Biophys Res Commun 294: 1009-1016.

30. Kovtun Y, Chiu WL, Tena G, Sheen J (2000) Functional analysis of oxidative stress-activated mitogen-activated protein kinase cascade in plants. Proc Natl Acad Sci U S A 97: 2940-2945.

31. Fowler S, Thomashow MF (2002) Arabidopsis transcriptome profiling indicates that multiple regulatory pathways are activated during cold acclimation in addition to the CBF cold response pathway. The Plant Cell 14: 1675-1690.

32. Thomashow MF1 (1999) PLANT COLD ACCLIMATION: Freezing Tolerance Genes and Regulatory Mechanisms. Annu Rev Plant Physiol Plant Mol Biol 50: 571-599.

33. Shinozaki K, Yamaguchi-Shinozaki K (2000) Molecular responses to dehydration and low temperature: differences and cross-talk between two stress signaling pathways. Curr Opin Plant Biol 3: 217-223.

34. Mizoguchi T, Irie K, Hirayama T, Hayashida N, Yamaguchi-Shinozaki K, et al. (1996) A gene encoding a mitogen-activated protein kinase kinase kinase is induced simultaneously with genes for a mitogen-activated protein kinase and an S6 ribosomal protein kinase by touch, cold, and water stress in Arabidopsis thaliana. Proc Natl Acad Sci USA 93: 765-769.

35. Ligterink W, Hirt H (2001) Mitogen-activated protein [MAP] kinase pathways in plants: versatile signaling tools. Int Rev Cytol 201: 209-275.

36. Posada J, Cooper JA (1992) Requirements for phosphorylation of MAP kinase during meiosis in Xenopus oocytes. Science 255: 212-215.

37. Marshall CJ1 (1994) MAP kinase kinase kinase, MAP kinase kinase and MAP kinase. Curr Opin Genet Dev 4: 82-89.

38. Jonak C, Kiegerl S, Ligterink W, Barker PJ, Huskisson NS, et al. (1996) Stress signaling in plants: a mitogen-activated protein kinase pathway is activated by cold and drought. Proc Natl Acad Sci U S A 93: 11274-11279.

39. Tallman G (1992) The chemiosmotic model of stomatal opening revisited. Crit Rev Plant Sci 11: 35-57.

40. Kearns EV, Assmann SM (1993) The Guard Cell-Environment Connection. Plant Physiol 102: 711-715.

41. Irving HR, Gehring CA, Parish RW (1992) Changes in cytosolic pH and calcium of guard cells precede stomatal movements. Proc Natl Acad Sci U S A 89: 1790-1794.

42. Hugouvieux V, Kwak JM, Schroeder JI (2001) An mRNA cap binding protein, ABH, modulates early abscisic acid signal transduction in Arabidopsis. Cell 106: 477-487.

43. Ingram J, Bartels D (1996) THE MOLECULAR BASIS OF DEHYDRATION TOLERANCE IN PLANTS. Annu Rev Plant Physiol Plant Mol Biol 47: 377-403.

44. Bray EA (1997) Plant responses to water deficit. Trends Plant Sci 2: 48-54.

45. Knight H, Knight MR (2001) Abiotic stress signalling pathways: specificity and cross-talk. Trends Plant Sci 6: 262-267.

46. Ichimura K, Mizoguchi T, Irie K, Morris P, Giraudat J, et al. (1998) Isolation of ATMEKK1 (a MAP kinase kinase kinase)-interacting proteins and analysis of a MAP kinase cascade in Arabidopsis. Biochem Biophys Res Commun 253: 532-543.

47. Ichimura K, Mizoguchi T, Yoshida R, Yuasa T, Shinozaki K (2000) Various abiotic stresses rapidly activate Arabidopsis MAP kinases ATMPK4 and ATMPK6. Plant J 24: 655-665.

48. Teige M, Scheikl E, Eulgem T, Dóczi R, Ichimura K, et al. (2004) The MKK2 pathway mediates cold and salt stress signaling in Arabidopsis. Mol Cell 15: 141-152.

49. Ichimura K, Casais C, Peck SC, Shinozaki K, Shirasu K (2006) MEKK1 is required for MPK4 activation and regulates tissue-specific and temperature-dependent cell death in Arabidopsis. J Biol Chem 281: 36969-36976.

50. Tamura T, Hara K, Yamaguchi Y, Koizumi N, Sano H (2003) Osmotic stress tolerance of transgenic tobacco expressing a gene encoding a membrane-located receptor-like protein from tobacco plants. Plant Physiol 131: 454-462.

51. Suzuki K, Shinshi H (1995) Transient Activation and Tyrosine Phosphorylation of a Protein Kinase in Tobacco Cells Treated with a Fungal Elicitor. Plant Cell 7: 639-647.

52. Stone JM, Walker JC (1995) Plant protein kinase families and signal transduction. Plant Physiol 108: 451-457.

53. Braam J, Davis RW (1990) Rain-, wind-, and touch-induced expression of calmodulin and calmodulin-related genes in Arabidopsis. Cell 60: 357-364.

54. Botella JR, Arteca RN (1994) Differential expression of two calmodulin genes in response to physical and chemical stimuli. Plant Mol Biol 24: 757-766.

55. Harding SA, Oh SH, Roberts DM (1997) Transgenic tobacco expressing a foreign calmodulin gene shows an enhanced production of active oxygen species. EMBO J 16: 1137-1144.

56. Hwang I, Sze H, Harper JF (2000) A calcium-dependent protein kinase can inhibit a calmodulin-stimulated Ca2+ pump (ACA2) located in the endoplasmic reticulum of Arabidopsis. Proc Natl Acad Sci U S A 97: 6224-6229.

57. Sheen J1 (1996) Ca2+-dependent protein kinases and stress signal transduction in plants. Science 274: 1900-1902.

58. Urao T, Katagiri T, Mizoguchi T, Yamaguchi-Shinozaki K, Hayashida N, et al. (1994) Two genes that encode Ca(2+)-dependent protein kinases are induced by drought and high-salt stresses in Arabidopsis thaliana. Mol Gen Genet 244: 331-340.

59. Saijo Y, Hata S, Kyozuka J, Shimamoto K, Izui K (2000) Over-expression of a single Ca2+-dependent protein kinase confers both cold and salt/drought tolerance on rice plants. Plant J 23: 319-327.

60. Kobayashi M, Ohura I, Kawakita K, Yokota N, Fujiwara M, et al. (2007) Calcium-dependent protein kinases regulate the production of reactive oxygen species by potato NADPH oxidase. Plant Cell 19: 1065-1080.

61. Martín ML, Busconi L (2000) Membrane localization of a rice calcium-dependent protein kinase (CDPK) is mediated by myristoylation and palmitoylation. Plant J 24: 429-435.

62. Hammond-Kosack KE, Jones JD (1996) Resistance gene-dependent plant defense responses. Plant Cell 8: 1773-1791.

63. Yang Y, Shah J, Klessig DF (1997) Signal perception and transduction in plant defense responses. Genes Dev 11: 1621-1639.

64. Zhang S, Klessig DF (1998) Resistance gene N-mediated de novo synthesis and activation of a tobacco mitogen-activated protein kinase by tobacco mosaic virus infection. Proc Natl Acad Sci U S A 95: 7433-7438.

65. Zhang S, Klessig DF (1998) The tobacco wounding-activated mitogen-activated protein kinase is encoded by SIPK. Proc Natl Acad Sci U S A 95: 7225-7230.

66. Freymark G, Diehl T, Miklis M, Romeis T, Panstruga R (2007) Antagonistic control of powdery mildew host cell entry by barley calcium-dependent protein kinases (CDPKs). Molecular Plant-Microbe Interactions 20: 1213-1221.

67. Zhang S, Klessig DF (1997) Salicylic acid activates a 48-kD MAP kinase in tobacco. Plant Cell 9: 809-824.

68. Zhang S, Du H, Klessig DF (1998) Activation of the tobacco SIP kinase by both a cell wall-derived carbohydrate elicitor and purified proteinaceous elicitins from Phytophthora spp. Plant Cell 10: 435-450.

69. Usami S, Banno H, Ito Y, Nishihama R, Machida Y (1995) Cutting activates a 46-kilodalton protein kinase in plants. Proc Natl Acad Sci U S A 92: 8660-8664.

70. Seo S, Okamoto M, Seto H, Ishizuka K, Sano H, Ohashi Y (1995) Tobacco MAP kinase: a possible mediator in wound signal transduction pathways. Science 270: 1988-1992.

71. Dietrich A, Mayer JE, Hahlbrock K (1990) Fungal elicitor triggers rapid, transient, and specific protein phosphorylation in parsley cell suspension cultures. J Biol Chem 265: 6360-6368.

72. Felix G, Grosskopf DG, Regenass M, Boller T (1991) Rapid changes of protein phosphorylation are involved in transduction of the elicitor signal in plant cells. Proc Natl Acad Sci U S A 88: 8831-8834.

73. Martin GB, Brommonschenkel SH, Chunwongse J, Frary A, Ganal MW, et al. (1993) Map-based cloning of a protein kinase gene conferring disease resistance in tomato. Science 262: 1432-1436.

74. Song WY, Wang GL, Chen LL, Kim HS, Pi LY, et al. (1995) A receptor kinase-like protein encoded by the rice disease resistance gene, Xa21. Science 270: 1804-1806.

75. Rommens CM, Salmeron JM, Oldroyd GE, Staskawicz BJ (1995) Intergeneric transfer and functional expression of the tomato disease resistance gene Pto. Plant Cell 7: 1537-1544.

76. Ronald PC, Salmeron JM, Carland FM, Staskawicz BJ (1992) The cloned avirulence gene avrPto induces disease resistance in tomato cultivars containing the Pto resistance gene. J Bacteriol 174: 1604-1611.

77. Salmeron JM, Staskawicz BJ (1993) Molecular characterization and hrp dependence of the avirulence gene avrPto from Pseudomonas syringae pv. tomato [corrected]. Mol Gen Genet 239: 6-16.

78. Salmeron JM, Oldroyd GE, Rommens CM, Scofield SR, Kim HS, et al. (1996) Tomato Prf is a member of the leucine-rich repeat class of plant disease resistance genes and lies embedded within the Pto kinase gene cluster. Cell 86: 123-133.

79. Wang XZ, Ron D (1996) Stress-induced phosphorylation and activation of the transcription factor CHOP (GADD153) by p38 MAP Kinase. Science 272: 1347-1349.

80. Pastuglia M, Roby D, Dumas C, Cock JM (1997) Rapid induction by wounding and bacterial infection of an S gene family receptor-like kinase gene in Brassica oleracea. Plant Cell 9: 49-60.

81. Pastuglia M, Ruffio-Châble V, Delorme V, Gaude T, Dumas C, et al. (1997) A functional S locus anther gene is not required for the self-incompatibility response in Brassica oleracea. Plant Cell 9: 2065-2076.

82. Asai T, Tena G, Plotnikova J, Willmann MR, Chiu WL, et al. (2002) MAP kinase signalling cascade in Arabidopsis innate immunity. Nature 415: 977-983.

83. Nühse TS, Peck SC, Hirt H, Boller T (2000) Microbial elicitors induce activation and dual phosphorylation of the Arabidopsis thaliana MAPK 6. J Biol Chem 275: 7521-7526.

84. Lu C, Han MH, Guevara-Garcia A, Fedoroff NV (2002) Mitogen-activated protein kinase signaling in postgermination arrest of development by abscisic acid. Proc Natl Acad Sci U S A 99: 15812-15817.

85. Yuasa T, Ichimura K, Mizoguchi T, Shinozaki K (2001) Oxidative stress activates ATMPK6, an Arabidopsis homologue of MAP kinase. Plant Cell Physiol 42: 1012-1016.

86. Desikan R, Hancock JT, Ichimura K, Shinozaki K, Neill SJ (2001) Harpin induces activation of the Arabidopsis mitogen-activated protein kinases AtMPK4 and AtMPK6. Plant Physiol 126: 1579-1587.

87. Apel K, Hirt H (2004) Reactive oxygen species: metabolism, oxidative stress, and signal transduction. Annu Rev Plant Biol 55: 373-399.

88. Laloi C, Apel K, Danon A (2004) Reactive oxygen signalling: the latest news. Curr Opin Plant Biol 7: 323-328.

89. Guan LM, Zhao J, Scandalios JG (2000) Cis-elements and trans-factors that regulate expression of the maize Cat1 antioxidant gene in response to ABA and osmotic stress: H2O2 is the likely intermediary signaling molecule for the response. Plant J 22: 87-95.

90. Nakagami H, Pitzschke A, Hirt H (2005) Emerging MAP kinase pathways in plant stress signalling. Trends Plant Sci 10: 339-346.

91. Matsuoka D, Nanmori T, Sato K, Fukami Y, Kikkawa U, Yasuda T (2002) Activation of AtMEK, an Arabidopsis mitogen-activated protein kinase kinase, in vitro and in vivo: analysis of active mutants expressed in E. coli and generation of the active form in stress response in seedlings. Plant J 29: 637-647.